Linking the MARKAL and REMI PI$^+$ Models

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Abstract

This paper intends to help the user analyze the interactions between the energy sector and the wider economy. This white paper strives to help the reader understand the integration of an economic-centered model, REMI PI$^+$, with an energy-focused forecasting model, MARKAL. Developed since 1980, REMI PI$^+$ is an eclectic macro-regional model that combines input-output, computer general equilibrium (CGE) and econometric models with New Economic Geography. MARKAL, developed in the 1970s, is a "bottom-up" energy-technology-environmental systems model, which provides an energy system perspective by simulating outputs under the constraints of minimizing aggregate system costs. MARKAL has been an effective tool for a variety of energy-related studies such as evaluating new technologies, energy policies, and quantifying emissions. In this case, REMI and MARKAL are integrated to answer "what-if" questions by constructing alternative scenarios and comparing them to the baseline forecast, which can capture the whole range of effects of new energy technology or policy, in its environmental, technological, and economic dimensions. MARKAL calculates key energy outputs that are considered exogenous input variables in the REMI model, such as fuel prices. These MARKAL outputs are then run through the REMI model's equations and linkages to forecast dynamic, year-by-year impacts on key sectors of the economy, such as output, employment, industry-specific impacts, and economically induced labor migration patterns. Together, the integrated REMI-MARKAL model provides a robust forecast of the development of new energy technologies and comprehensive impact analyses of the environmental, economic, and technological costs and benefits of energy polices. This total integration of economic and environmental impacts makes for a state-of-the-art tool in energy policy analysis and decision-making.

Glossary

Demand: In MARKAL, the words 'demand' and 'output' are used equivalently in the case of end-use energy services, since imports/exports are not distinguished for these sub-sectors. In REMI PI^+, and in MARKAL, energy supply sub-sector 'demand' refers to the local demand, excluding exports/imports.

Growth factor: ratio of some quantity in year t over the same in reference year 0

Growth rate (annual): Average annual growth in percent over t years, i.e.
$100*[(Quantity(t)/Quantity(0))^{1/t} - 1]$

Industry: in REMI PI^+, the term encompasses an industrial (or commercial) sector activity. The most disaggregated list of REMI PI industries corresponds to the 4-digit NAICS classification. In MARKAL, the industrial sector does not include commercial and residential entities, which are represented in their own sectors. MARKAL has many fewer distinct industries than REMI PI^+. Only a handful of energy intensive industries are individually represented, all others being regrouped under the "Other Industries" catch-all category.

Output: In REMI PI^+, this refers to the production of a particular sub-sector. In MARKAL, it refers to end-use energy services.

Output (nominal): REMI PI^+ output expressed as physical quantity multiplied by current price.

Output (real): REMI PI^+ output expressed as physical quantity multiplied by price in some fixed reference year. The growth in real output is the same as the growth in physical quantity.

Sub-sector: word used to designate an industry, a group of industries, or a specified portion of household activity such as car travel, housing, mass transit, etc. The extent of a sub-sector varies depending on the degree of disaggregation of the particular model concerned.

Table of Contents

I. OVERVIEW OF THE REMI MODEL

REMI PI+ captures industry-specific impacts beyond a benefit-cost ratio by integrating input-output tables (I-O models), computable general equilibrium theory (CGE), econometric estimates, and New Economic Geography (NEG). PI+ also allows custom-designed scenarios to gauge the full impact of Renewable Portfolio Standard (RPS), overcoming the limitation of available data by creating alternative, full cost-recovery scenarios. In addition, the dynamic model captures interstate trade flows and year-by-year population migration, which distinguishes net new economic activities from relocation of existing economic activity, as well as short-term impacts in comparison to long-term results.

(1) **Output and Demand** consist of output, demand, consumption, investment, government spending, exports and imports, as well as feedback from output changes due to the change in the productivity of intermediate inputs.

(2) **Labor and Capital Demand** include the determinants of labor productivity, labor intensity, and the optimal capital stocks.

(3) **Population and Labor Supply** include labor force participation and the economic migration equation, where demography responds to economic factors.

(4) **Compensation, Prices, and Costs** include composite prices, determinants of production costs, the consumption price deflator, housing prices, and the compensation equation.

(5) **Market Shares** consist of proportion of local, inter-regional, and export markets captured by each region. *Figure 1.1* contains all model blocks, their components, and linkages without the New Economic Geography linkages, which *Figure 1.2* highlights.

The inherent linkages capture exogenous shocks by tracing their ripple and feedback effects throughout the macro-economy, reflecting impacts on not only the sectors and regions directly affected by the policy shift, but all industries and regions nationwide.

Figure 1.1 – REMI model diagram (excluding New Economic Geography linkages)

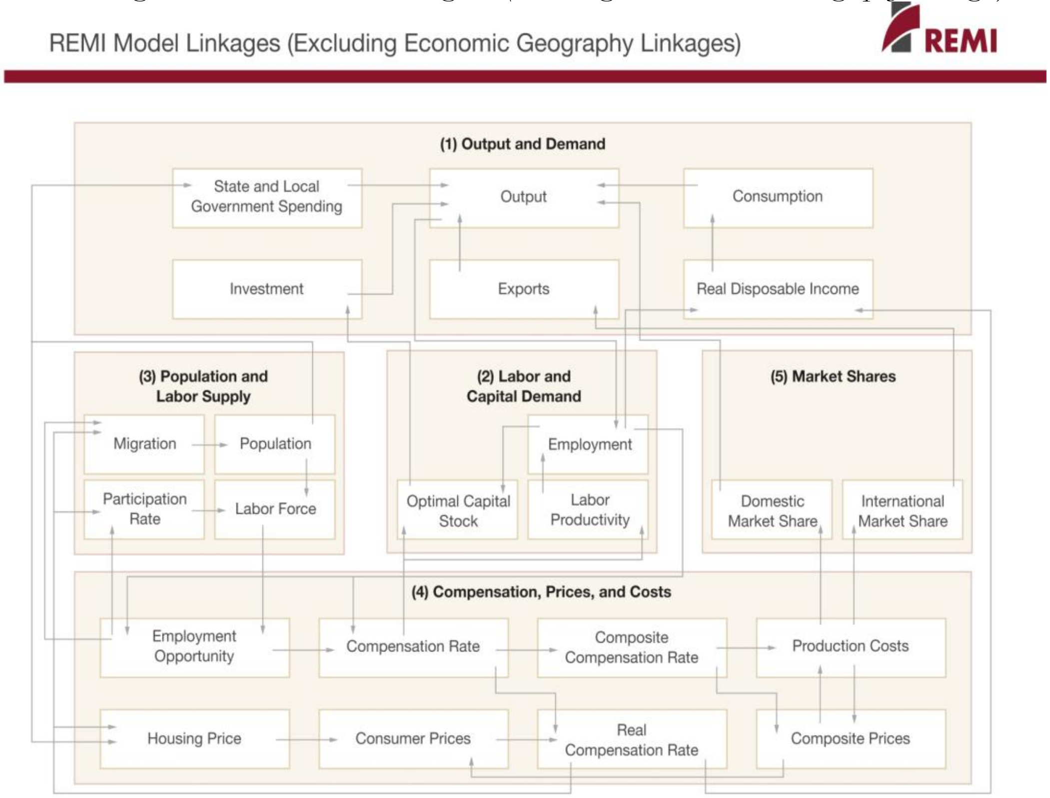
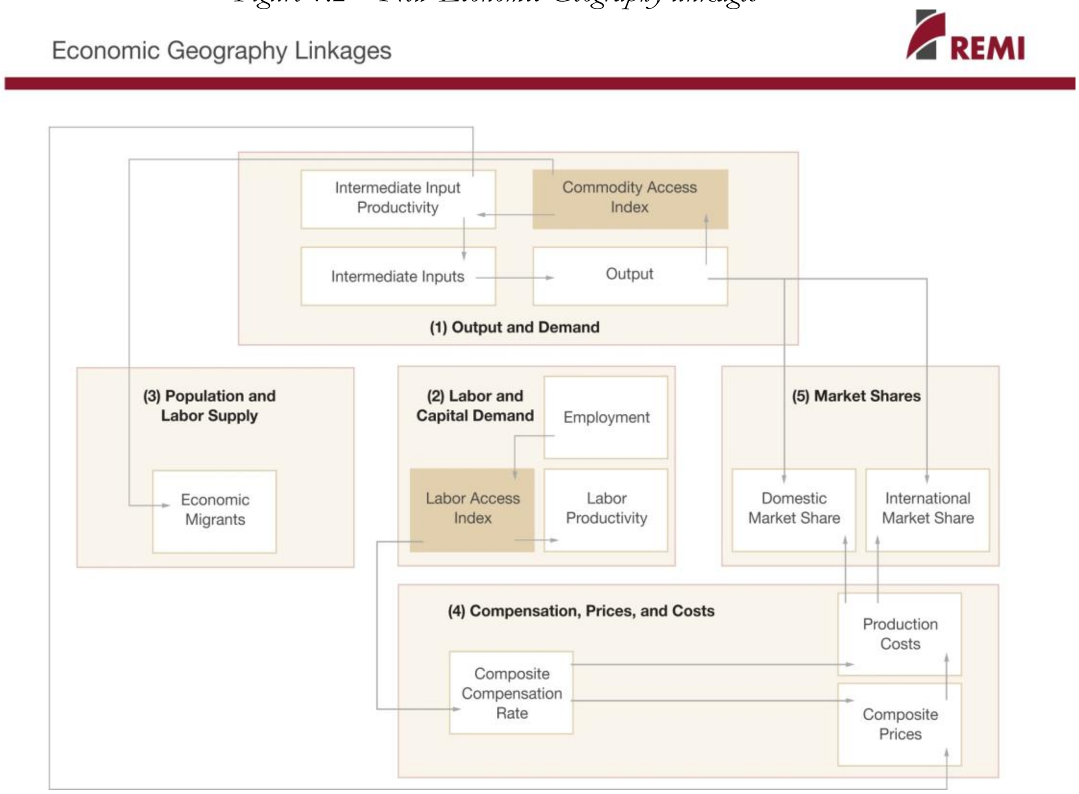


Figure 1.2 – New Economic Geography linkages



With the continuous development since 1980, REMI models have been used by regional and local governments, academic institutions, consulting firms as well as planning committees both in the United States and abroad for a variety of studies, including energy and the environment, transportation, economic development, taxation, forecasting and planning. Example studies include, the Massachusetts Department of Revenue who used the model to assess the states film tax credit program, the Center for Automotive Research who did an economic impact analysis of the bankruptcy of the "Big Three" automakers in Detroit, Michigan, and West Virginia University who looked at the economic impacts of the Kyoto Protocol on West Virginia's economy. REMI creates a simulation scenario and compares it against business-as-usual forecast (BAU) to compare the differences between a certain policy implementation and an alternative situation, creating an "apples-to-apples" comparison with all other variables in the baseline forecast *ceteris paribus*.

II. OVERVIEW OF THE MARKAL MODEL

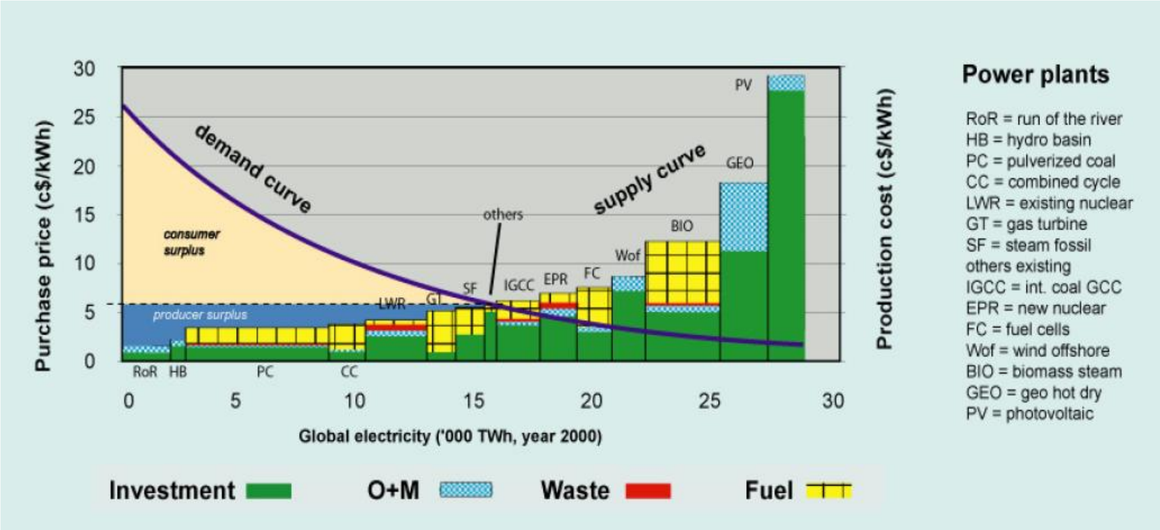
MARKAL stands for MARKet ALlocation, and was developed in the late 1970s at Brookhaven National Lab in response to the OPEC oil embargo. MARKAL was further adopted and developed by the International Energy Agency under the Energy Technology and Systems Analysis Program (ETSAP), and more recently by the U.S. Department of Energy's (DOE) Energy Information Administration (EIA) as the basis for its System for the Analysis of Global Energy Markets (SAGE) model to produce EIA's annual International Energy Outlook. Altogether, MARKAL and its variants are used in approximately 70 countries around the world.

MARKAL is a data-driven, energy system optimization model. The user inputs the structure of the energy system, including resource supplies, energy conversion technologies, end-use demands, and the technologies used to satisfy these demands. In addition, the user is required to characterize each of the technologies and resources used, including fixed and variable costs, technology availability and performance, and pollutant emissions. MARKAL then calculates, using straightforward linear and mixed-integer linear programming techniques, the least cost set of technologies over time to satisfy the specified demands, subject to various user-defined constraints. Outputs of the model include a determination of the technological mix at intervals into the future, estimates of total system cost, energy demand (by type and quantity), estimates of criteria and GHG emissions, and estimates of energy commodity prices.

MARKAL has been widely applied in studying energy and environmental economics, such as mitigation, emission, and regulation impact analysis (RIA) renewable fuel standard policy. MARKAL has also been used as an economic impact analysis tool both as a stand-alone model and integrated with other models. When used in conjunction with economic models, MARKAL overcomes the limitations of economic models with its high level of technological detail and representation of large sources of criteria and greenhouse gas (GHG) emissions. In addition, MARKAL provides the appropriate sector level detail, overcoming the abstraction of single energy sector models and the excessive aggregation of multi-sector models. MARKAL is also an effective tool in evaluating environmental and economic impacts related to climate change due to its ability to conduct multi-pollutant analyses, which makes it easy to identify strategies that target many pollutants at lower costs, instead of single-pollutant reduction approach.

MARKAL analysis constructs three scenarios: high-emission, baseline emission, and low-emission. The high-emission scenario includes higher health impacts of emissions and benefit from emissions reduction, as well as higher costs of achieving emission reductions. The baseline emission includes baseline costs and benefits. The low-emission scenario includes lower health impacts of emissions and the benefits from emissions reduction, as well as lower costs of achieving emissions reductions.

MARKAL models energy prices as equilibrium point of technical-economic (inverse) supply – demand curves as illustrated in the following graph.



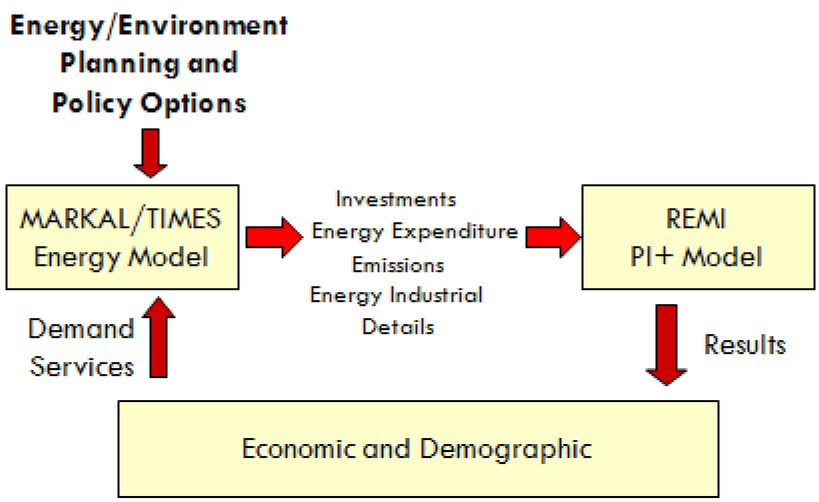
Typical representation of an energy commodity in MARKAL - TIMES.
The algorithm maximises the global surplus over thousands such markets.

The graph illustrates the market clearing prices for a wide variety of energy sources. The costs of production of each energy source consist of investment cost, operation and management (O & M) costs, waste cost and fuel cost. The price is determined by the intersection of technical-economic inverse demand curve and supply curves of different types of energy.

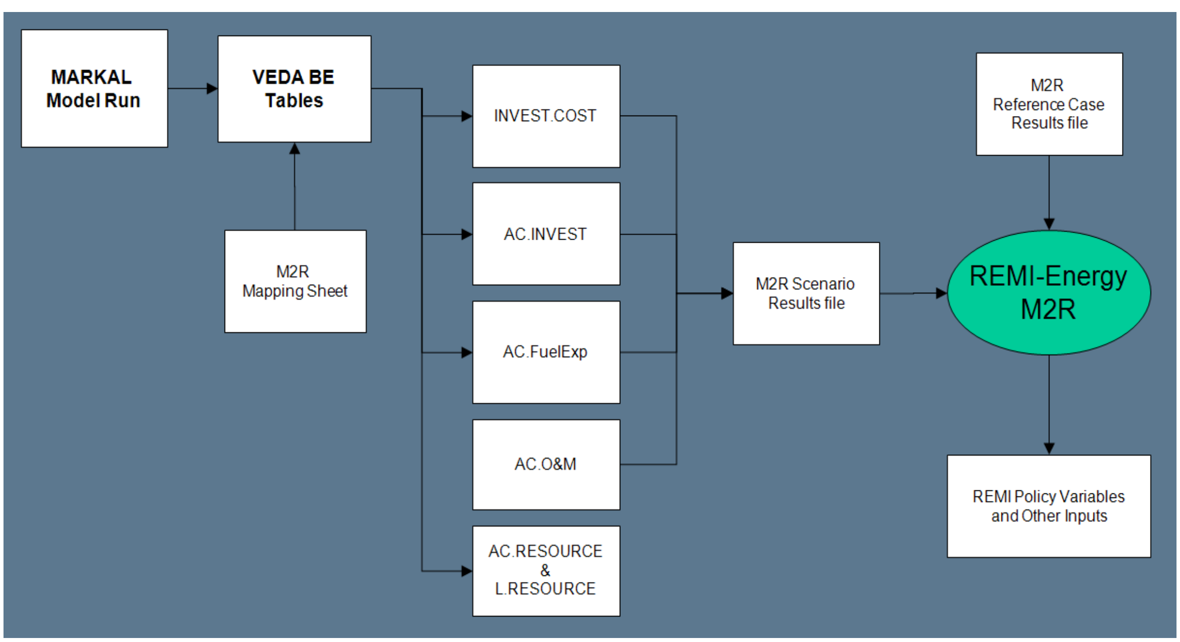
The MARKAL model has been applied by the International Energy Agency (IEA) in its Energy Technology Perspectives (ETP) project and provided technology detail to World Energy Outlook scenarios. MARKAL's successor, ETSAP TIMES Integrated Assessment Model (TIAM) has contributed to the development of hedging strategies and UNFCCC (United Nations Framework Convention on Climate Change) working group III. MARKAL has also been applied extensively to global studies and forecasts, such as the Asian Development Bank sponsored Pakistan Integrated Assessment Model and the UK Department of Trade and Industry for "Options for a Low Carbon Future – Phase 2 + 3" analysis.

III. REMI-MARKAL INTEGRATION

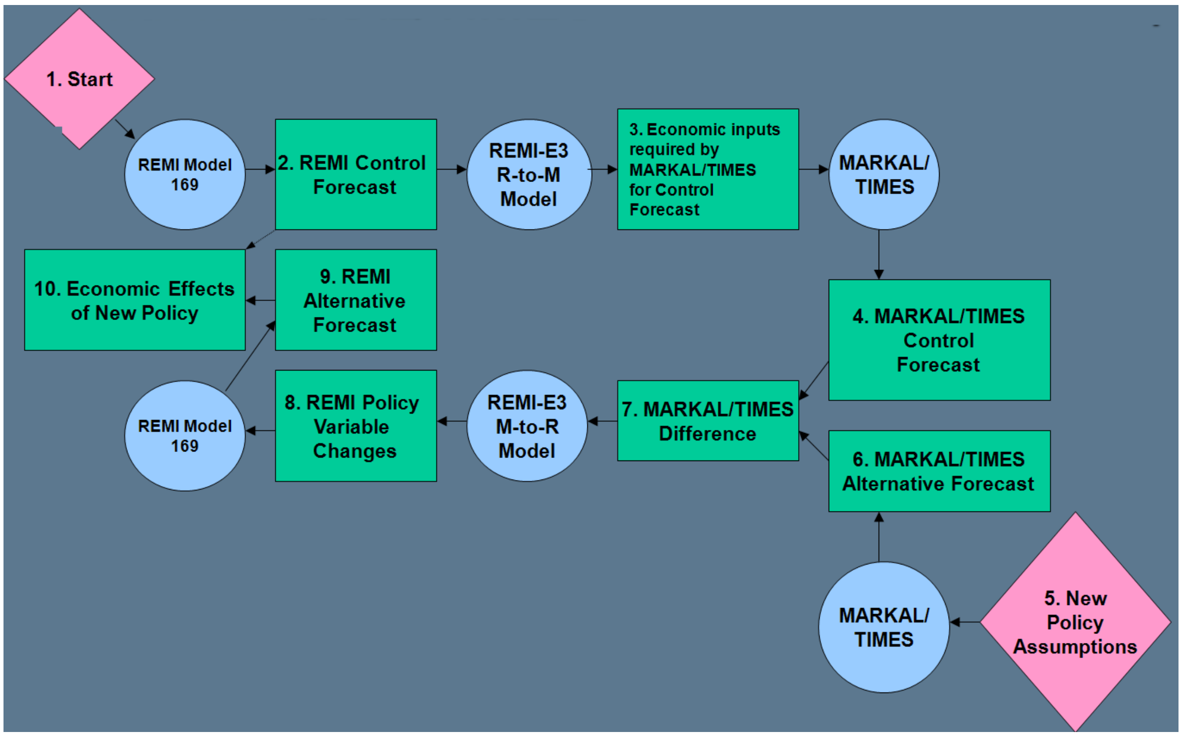
The models REMI and MARKAL can be integrated both ways. On one hand, REMI can provide economic and demographic parameters for the MARKAL reference scenario. On the other hand, MARKAL can simulate specific energy/environmental policies, generating output variables such as investments, energy expenditures, emissions, as well as energy industrial details that can be used in REMI and to calculate detailed economic impacts of MARKAL results. Together, MARKAL and REMI can identify economic, environmental and technological impacts of projects, as well as identify the most effective policy options excelling in all above areas. The following graph illustrates the integration of MARKAL/TIMES energy model and REMI PI^{+} model and the double-direction interaction between the data inputs/outputs.



More specifically, integration can be done in the direction of M2R (MARKAL to REMI), where the REMI model could integrate inputs such as investment, fuel expenses, operation, and management costs from MARKAL. This calibrates REMI's baseline forecast and then constructs an alternative forecast with policy variables in REMI, delivering results on economic impacts of environmental and technological inputs, as illustrated in the graph below.

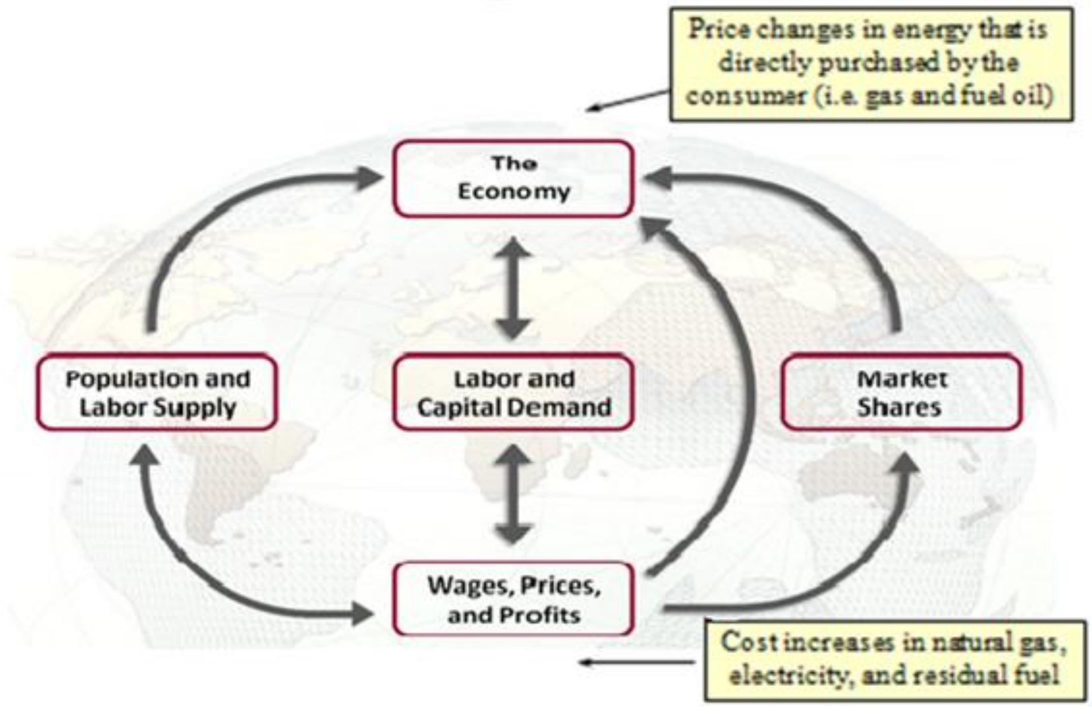


The user runs the MARKAL model first, prepares VEDA BE tables with inputs from the M2R Mapping Sheet, calculates investment cost, AC invest, AC fuel expenses, AC Operation & management cost, AC resource & L resource and then compiles them into an M2R Scenario Results File. The REMI-Energy M2R model then uses this MARKAL input to build a reference case, and run its own policy variables classified by four-digit NAICS code and constructs an alternative scenario for new energy policies or technology. Likewise, a model can also be constructed in the direction of (R2M) REMI to MARKAL.



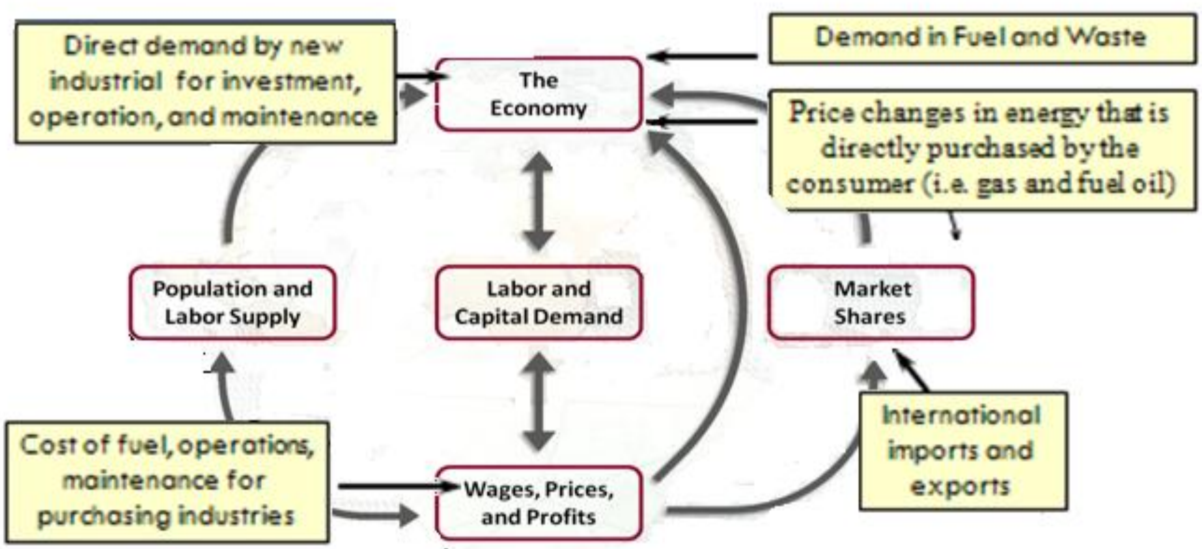
First, REMI's 169-sector model constructs a control forecast with economic inputs required by the MARKAL model, which is then built into the control forecast of MARKAL. An alternative forecast is generated by MARKAL, and the difference between the MARKAL control forecast and the MARKAL alternative forecast is run through the REMI-MARKAL M-to-R model, interpreted with REMI policy variable changes, and a REMI alternative forecast made illustrating the economic effects of new policy.

The REMI-MARKAL system has different levels of integration. At the most basic level, MARKAL precisely calculates the prices and costs of various types of energy that REMI PI$^+$ takes as exogenous, as illustrated in the following graph.



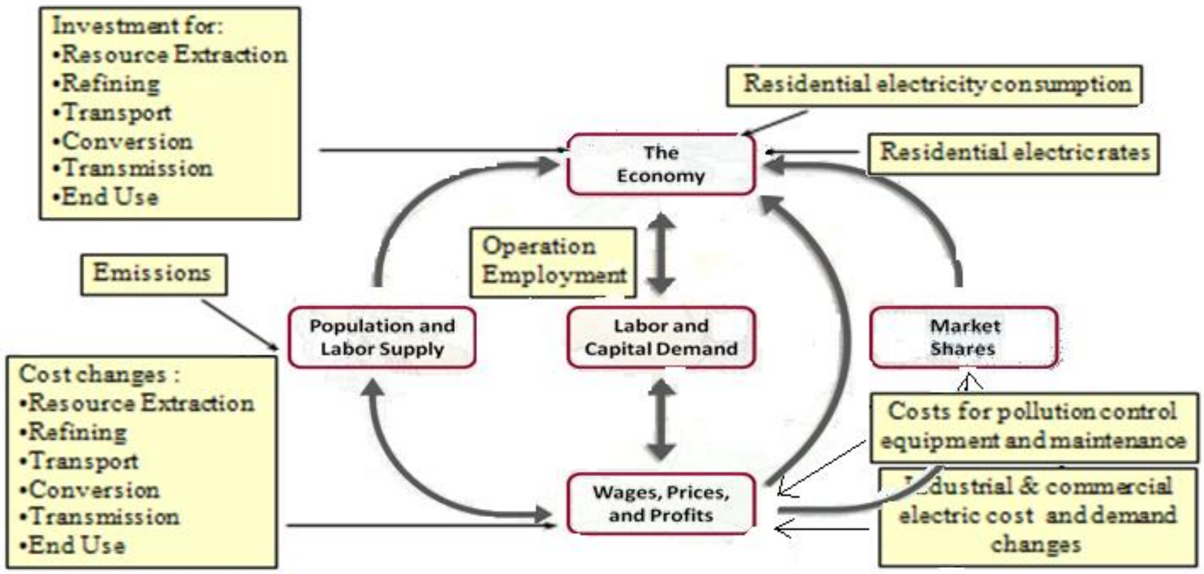
MARKAL calculates price changes in energy directly purchased by consumers, which is then treated as an input variable in the **Output** block of the REMI model. Likewise, cost increases in natural gas, electricity, and residual fuel as results from the MARKAL model can also be inputted into the **Wages, Costs & Prices** block.

In addition, demand for new energy establishments or industries can be captured by MARKAL in terms of **investment** as well as **fuel and waste**, both of which affect **Output** in the REMI model.



At a greater level of detail, MARKAL can also input **investment, and operation and maintenance** in the energy sector as well as in the **imports/exports** sector to the REMI inputs, as illustrated in the following graph.

Furthermore, both **investments** and **costs** in the energy sector can be further broken down into categories, demand in fuel further analyzed by end-user, and their induced impact on **operation and employment** of the energy sector, as in the following graph:



Both investments and cost changes are broken down to the following categories: **Resource Extraction, Refining, Transport, Conversion, Transmission**, and **End Use**. Different types of energy investment affect **output**, while cost changes affect **Wages, Costs and Prices** in the REMI model. In addition, **Output** also responds to changes in **Residential electricity consumption and Residential electricity rates**, and **Operation and Employment** induced by changes in the energy sector and captured by MARKAL model. In addition, **Wages, Costs and Prices** respond to **Industrial and Commercial Electric cost and demand changes** and **Costs for pollution control equipment and maintenance changes** captured by MARKAL model. **Emissions** can be calculated by the MARKAL model and its economic costs inputted into REMI PI+ on factors such as **labor and population**.

The combined inputs can then be used to conduct economic impact analysis to take a close-up look at impacts of changes in the energy sector on employment, output, and economically induced migration (termed as Economic Migration) in the PI^+ model, bridging energy sector analysis and economic theory with policy impacts.

IV. TECHNICAL MEMORANDUM

MARKAL

The technical details provided below are not meant to be an exhaustive list of MARKAL characteristics, but rather to highlight the relevant ones to the REMI-MARKAL integration. If needed, a full description of the generic MARKAL model is contained in the MARKAL documentation available from, <www.iea-etsap.org/web/Documentation.asp>.

MARKAL (an acronym for MARKet ALlocation) is a mathematical model of the energy system of one or several regions that provides a technology-rich basis for estimating energy dynamics over a multi-period horizon. The user must provide Reference case estimates of end-use energy service demands (e.g., car, commercial truck, and heavy truck road travel; residential lighting; steam heat requirements in the paper industry, etc.). The user would create the Reference based on economic and demographic projections, possibly for each individual region in a multi-region formulation of the model. (Table 1 contains the list of the energy services represented in the U.S. EPA national MARKAL model (EPA-NM) of the entire USA.) In addition, the user provides estimates of the existing stock of energy related equipment, and the characteristics of available future technologies, as well as new sources of primary energy supply and their potentials, in all sectors of the energy system.

MARKAL Sectors and Sub-Sectors

The MARKAL sectors are:

- Primary energy supply
    - Sub-sectors: production of coal, oil, natural gas, biomass, nuclear, wind, geothermal, solar, and hydro resources
- Secondary processing of energy
    - Sub-sectors: production of refined petroleum products, pipeline gas, prepared coal, alcohols, hydrogen
- Energy conversion into electricity and low temperature heat
- End-use energy consuming sectors: industry, transportation, commercial and residential buildings. Each end-use sector is further differentiated into sub-sectors, each driven by a different energy service demand (see Table 1).

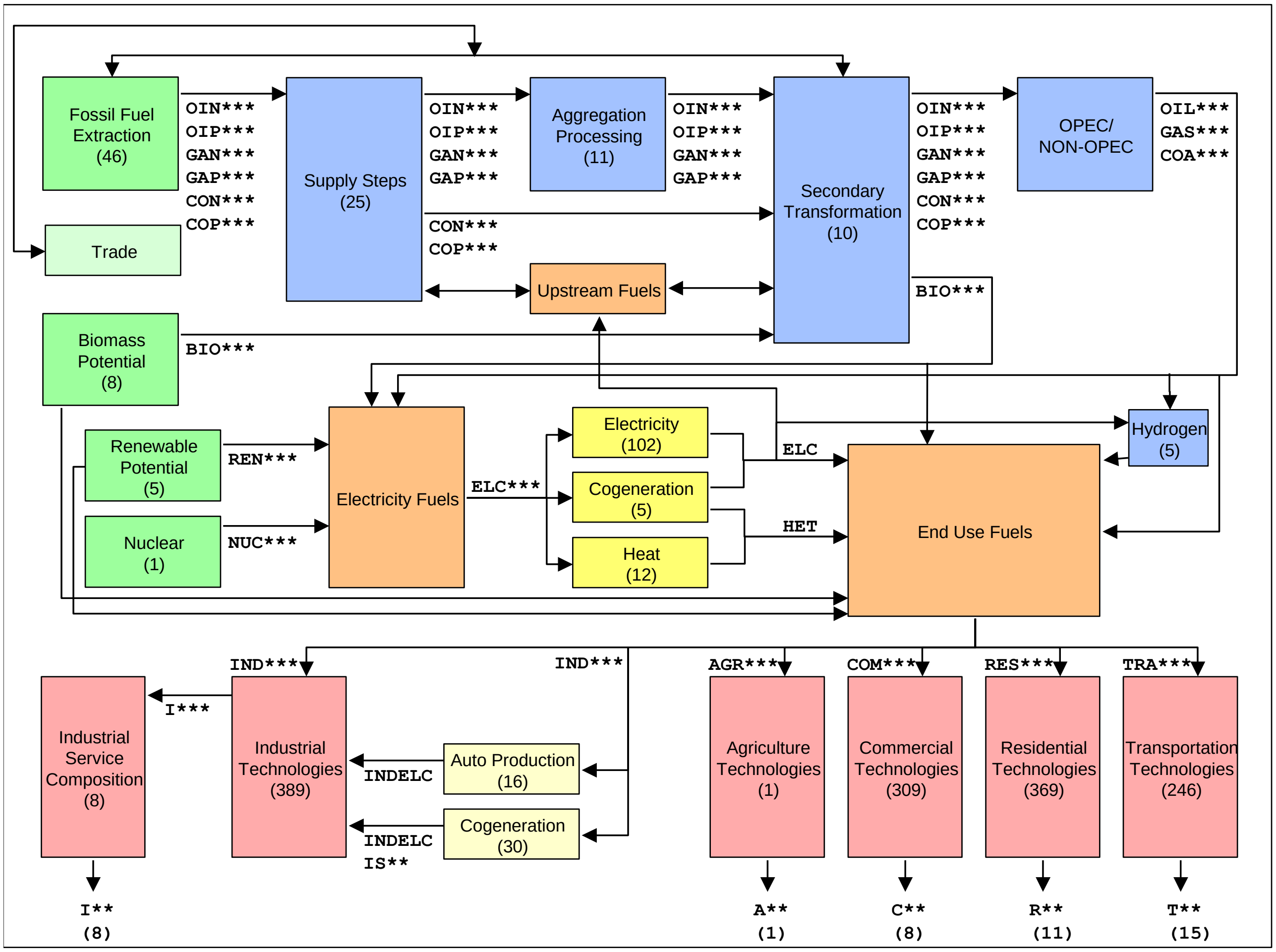
Table 1: List of U.S. EPA-MARKAL demand categories

Sector	Demand Category (sub-sectors)
Buildings (21 categories)	
	Residential space cooling
	Residential freezers
	Residential space heating
	Residential lighting
	Residential miscellaneous electric
	Residential miscellaneous gas
	Residential refrigeration
	Residential water heating
	Commercial Space Cooling
	Commercial Computer and Office Equipment
	Commercial Space Heating Services
	Commercial Cooking Services
	Commercial Lighting Services
	Commercial Miscellaneous - Diesel
	Commercial Miscellaneous - Electricity
	Commercial Miscellaneous - Natural gas
	Commercial Miscellaneous - LPG
	Commercial Miscellaneous - Residual fuel
	Commercial Refrigeration Services
	Commercial Ventilation Services
	Commercial Water Heating Services
Transport (7 categories)	
	All air transport service demand (seat miles)
	Bus services (vmt)
	Heavy trucks greater than 10,000 lbs (vmt)
	Personal automotive (LDV) services (vmt)
	Freight services by rail (ton miles)
	Passenger services by rail
	Marine energy services
Industry (6 categories)	
	Chemicals
	Non Metals
	Non-ferrous metals
	Iron and Steel
	Pulp and Paper
	Other Industries
TOTAL : 34 categories	

The MARKAL Reference Energy System

Each MARKAL sub-sector is represented by a (usually) large number of technologies, each producing, and/or consuming, a variety of energy forms. The complete representation of all technologies and energy forms linking them is called the Reference Energy System (RES). Technologies are traditionally represented by boxes or nodes, and energy forms by links. The schematic representation of the MARKAL RES is shown in Figure 2.1. Each box in the diagram may contain a large number of technologies. The data on existing and future technologies in each sector constitutes the techno-economic database of the model, which may contain detailed data on thousands of technologies.

Figure 2.1: Simplified Reference Energy System (RES)



Economic Rationale-MARKAL

MARKAL computes energy balances at all levels of an energy system: primary resources, secondary fuels, final energy, and energy services. The model aims to supply energy services at the minimum overall system cost by simultaneously making equipment investment and operating decisions, and primary energy supply decisions, by each region. For example, in MARKAL, if there is an increase in residential lighting energy service demand, (perhaps due to a decline in the cost of residential lighting), either existing generation equipment must be used more intensively or new equipment must be installed (or both). The choice of generation equipment (type, fuel and timing) incorporates consideration of the characteristics of alternative generation technologies and the economics of primary energy supply, as well as options such as conservation, energy efficiency improvements and other demand side actions. MARKAL is thus a vertically integrated model of the entire energy system.

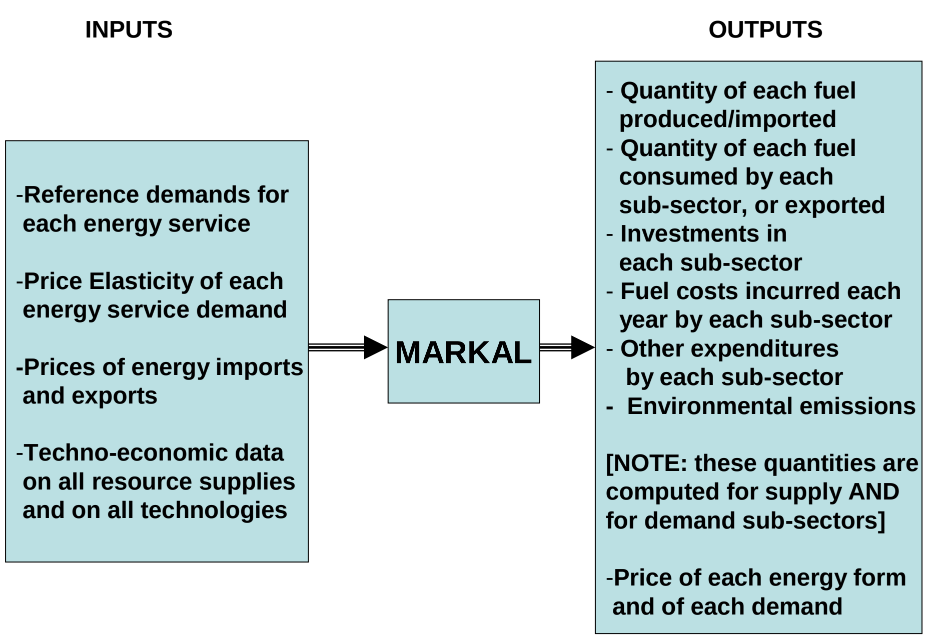
In identifying a least-cost solution, MARKAL computes an inter-temporal partial equilibrium on energy markets. This means first that MARKAL computes the quantities and prices for each energy form, and second that the quantities and prices of the various fuels and other commodities are in equilibrium, i.e. their prices and quantities in each time period are such that at those prices the markets are cleared. Suppliers produce exactly the quantities demanded by the consumers. Further, this equilibrium has the property that the total surplus is maximized over the entire modeled time horizon. Such a criterion is equivalent to minimizing the discounted total system cost over the time horizon. Investments made at any given period are optimal over the horizon as a whole, thanks to the perfect foresight characteristic of the model.

MARKAL Inputs and Outputs

On the inputs side, the core techno-economic data on each MARKAL technology includes efficiency, utilization factor, start year, technical life, emissions factors for several substances, capital cost and fixed and variable annual costs (however, the latter are not subdivided into labor and other annual costs). Fuel costs are not an exogenous MARKAL parameter; rather, fuel costs are endogenously computed by the model as the quantity of fuel used multiplied by their calculated fuel price. Figure 2.2 summarizes the inputs and outputs of the MARKAL model. These will be essential in devising the linkages.

Regarding MARKAL outputs, the primary outputs are the quantities of fuels produced and consumed, the technological investments, other annual expenditures, the fuel prices, the cost of meeting the next unit of each demand service, and emission levels. The other outputs (fuel costs) are indirectly obtained from the primary outputs (i.e. fuel costs = price x quantities).

Figure 2.2: Inputs and outputs of the MARKAL model



REMI
The technical details provided below are not meant to be an exhaustive list of REMI characteristics, but rather to highlight the relevant ones to the REMI-MARKAL integration. If needed, a full description of the generic REMI model is contained in the REMI documentation available from, <www.remi.com>.

In this report, we shall not be directly concerned with the geographic aspects of REMI PI^+. Thus, the reference case would consider a one-region PI^+ model such as the entire U.S. or a single state or county. However, the geographic aspects of REMI PI^+ may be very useful in specific applications, such as in projecting energy service demands at a state or regional scale, or in multi-regional versions of the MARKAL model (e.g., NE-MARKAL).

REMI PI^+ Sub-Sectors
In REMI PI^+, the resolution is at the level of each individual industry. There are 169 industries in REMI PI^+ version 1.3, corresponding approximately with the four-digit NAICS classification (all 169 sectors are shown in Table 2). Each industry has its own output (a product or service). An I/O matrix establishes the dollar input to industry $\boldsymbol{i}$ required for one dollar output of industry $\boldsymbol{j}$. Inputs and outputs are expressed in real terms[1]. In addition, the household consumption is split into 13 distinct categories (Table 3), and each category is further broken down into the 169 industries via a *bridge matrix* $\{\boldsymbol{b_{ij}}\}$ where $\boldsymbol{b_{ij}}$ is the fractional content of one unit of consumption $\boldsymbol{i}$ that is an input from industry $\boldsymbol{j}$. Therefore, the 13 consumption categories eventually map into 169 product categories.

[1] Real output is the output in physical units multiplied by its price at some fixed reference year. Therefore, the growth of the physical output is identical to the growth of the real output. Furthermore, since real outputs are additive (since they are expressed in the same $ units), it is perfectly correct to add together the outputs of several REMI industries in order to obtain the real output of some aggregated sector.

Table 2: List of 169 REMI PI+ industries

Forestry; Fishing, hunting, trapping	Ship and boat building	Data processing, hosting, related services, and other information services
Logging	Other transportation equipment manufacturing	Broadcasting (except internet)
Support activities for agriculture and forestry	Household and institutional furniture and kitchen cabinet manufacturing	Telecommunications
Oil and gas extraction	Household and institutional furniture and kitchen cabinet manufacturing	Monetary authorities, credit intermediation, and related activities
Coal mining	Office furniture (including fixtures) manufacturing	Funds, trusts, and other financial vehicles
Metal ore mining	Other furniture related product manufacturing	Securities, commodity contracts, and other financial investments and related activities
Nonmetallic mineral mining and quarrying	Medical equipment and supplies manufacturing	Insurance carriers
Support activities for mining	Other miscellaneous manufacturing	Agencies, brokerages, and other insurance related activities
Electric power generation, transmission, and distribution	Animal food manufacturing	Real estate
Natural gas distribution	Grain and oilseed milling	Automotive equipment rental and leasing
Water, sewage, and other systems	Sugar and confectionery product manufacturing	Consumer goods rental and general rental centers
Construction	Fruit and vegetable preserving and specialty food manufacturing	Commercial and industrial machinery and equipment rental and leasing
Sawmills and wood	Dairy product	Lessors of nonfinancial intangible

preservation	manufacturing	assets (except copyrighted works)
Veneer, plywood, and engineered wood product manufacturing	Animal slaughtering and processing	Legal services
Other wood product manufacturing	Seafood product preparation and packaging	Accounting, tax preparation, bookkeeping, and payroll services
Clay product and refractory manufacturing	Bakeries and tortilla manufacturing	Architectural, engineering, and related services
Glass and glass product manufacturing	Other food manufacturing	Specialized design services
Cement and concrete product manufacturing	Beverage manufacturing	Computer systems design and related services
Lime, gypsum product manufacturing; Other nonmetallic mineral product manufacturing	Tobacco manufacturing	Management, scientific, and technical consulting services
Iron and steel mills and ferroalloy manufacturing	Fiber, yarn, and thread mills	Scientific research and development services
Steel product manufacturing from purchased steel	Fabric mills	Advertising and related services
Alumina and aluminum production and processing	Textile and fabric finishing and fabric coating mills	Other professional, scientific, and technical services
Nonferrous metal (except aluminum) production and processing	Textile furnishings mills	Management of companies and enterprises
Foundries	Other textile product mills	Office administrative services; Facilities support services
Forging and stamping	Apparel knitting mills	Employment services
Cutlery and hand tool manufacturing	Cut and sew apparel manufacturing	Business support services; Investigation and security services; Other support services
Architectural and structural	Apparel accessories and	Travel arrangement and reservation

metals manufacturing	other apparel mfg.	services
Boiler, tank, and shipping container manufacturing	Leather, hide tanning, finishing; Other leather, allied product manufacturing	Services to buildings and dwellings
Hardware manufacturing	Footwear manufacturing	Waste management and remediation services
Spring and wire product manufacturing	Pulp, paper, and paperboard mills	Elementary and secondary schools; Junior colleges, colleges, universities, and professional schools; Other educational services
Machine shops; turned product; and screw, nut, and bolt manufacturing	Converted paper product manufacturing	Offices of health practitioners
Coating, engraving, heat treating, and allied activities	Printing and related support activities	Outpatient, laboratory, and other ambulatory care services
Other fabricated metal product manufacturing	Petroleum and coal products manufacturing	Home health care services
Agriculture, construction, and mining machinery manufacturing	Basic chemical manufacturing	Hospitals
Industrial machinery manufacturing	Resin, synthetic rubber, and artificial synthetic fibers and filaments manufacturing	Nursing and residential care facilities
Commercial and service industry machinery manufacturing	Pesticide, fertilizer, and other agricultural chemical manufacturing	Individual, family, community, and vocational rehabilitation services
Ventilation, heating, air-conditioning, and commercial refrigeration equipment manufacturing	Pharmaceutical and medicine manufacturing	Child day care services
Metalworking machinery manufacturing	Paint, coating, and adhesive manufacturing	Performing arts companies; Promoters of events, and agents and managers
Engine, turbine, power transmission equipment	Soap, cleaning compound, and toilet preparation	Spectator sports

manufacturing	manufacturing	
Other general purpose machinery manufacturing	Other chemical product and preparation manufacturing	Independent artists, writers, and performers
Computer and peripheral equipment manufacturing	Plastics product manufacturing	Museums, historical sites, and similar institutions
Communications equipment manufacturing	Rubber product manufacturing	Amusement, gambling, and recreation industries
Audio and video equipment manufacturing	Wholesale trade	Accommodation
Semiconductor and other electronic component manufacturing	Retail trade	Food services and drinking places
Navigational, measuring, electromedical, and control instruments manufacturing	Air transportation	Automotive repair and maintenance
Manufacturing and reproducing magnetic and optical media	Rail transportation	Electronic and precision equipment repair and maintenance
Electric lighting equipment manufacturing	Water transportation	Commercial and industrial equipment (except automotive and electronic) repair and maintenance
Household appliance manufacturing	Truck transportation	Personal and household goods repair and maintenance
Electrical equipment manufacturing	Couriers and messengers	Personal care services
Other electrical equipment and component manufacturing	Transit and ground passenger transportation	Death care services
Motor vehicle manufacturing	Pipeline transportation	Dry cleaning and laundry services
Motor vehicle body and trailer manufacturing	Scenic and sightseeing transportation and support activities for transportation	Other personal services

Motor vehicle parts manufacturing	Warehousing and storage	Religious organizations; Grantmaking and giving services, and social advocacy organizations
Aerospace product and parts manufacturing	Newspaper, periodical, book, and directory publishers	Civic, social, professional, and similar organizations
Railroad rolling stock manufacturing	Software publishers	Private households
	Motion picture, video, and sound recording industries	

Table 3: List of REMI PI+ consumption categories

Vehicles & Parts
Computers & Furniture
Other Durables
Food & Beverages
Clothing & Shoes
Gasoline & Oil
Fuel Oil & Coal
Other Non-Durables
Housing
Household Operation
Transportation
Medical Care
Other Services

Note: these 13 categories are further broken down into 169 industrial products via a Bridge matrix

Economic Rationale-REMI

REMI PI+ is a hybrid economic model that combines four quantitative methodologies (input-output, econometric, computable general equilibrium, and new economic geography) to create a complete and robust economic and demographic model. REMI PI+ is a geographic model where labor, capital, and investments may migrate between regions within a competitive setting where each region competes with all others for market shares of all products. Capital is assumed to migrate instantaneously, while labor is subject to lags and delays. Land is a fixed commodity in each region.

Products may be shipped from any region to any other region, with a transportation cost. The general organization of the REMI PI$^+$ model is shown in Figure 1.1 and 1.2.

Outputs and demands: demands for the various products are endogenously computed as part of a general equilibrium. They are a function of income and of product prices. Each product has a price, also computed endogenously. Each industry's output is the sum of demand, intermediate input (to other industries), and net exports (exports minus imports).
Land, capital, labor: three additional factors are not endogenously produced: total labor supply is calculated from population statistics; capital is implicitly formed from savings, which are part of household income, but may also be raised abroad; and, land is of course fixed in each region, but its price may evolve according to demand.
Consumption: the part of income not going to savings is used for consumption of the 13 categories, which themselves are further broken down to the 169 industrial products.
Costs, wages: product costs are computed as functions of prices of inputs (other products, land, labor, capital), output levels, and investments. Prices of all products and commodities (product prices, cost of capital, land price, and wage rate) are also endogenously determined.

The Inputs and Outputs of the REMI PI$^+$ Model
To compute a Reference forecast, REMI PI$^+$ uses the following types of inputs:

- Population statistics such as base year population, death and birth rates, etc;
- The I/O matrix of coefficients, where energy inputs per unit of each product are part of the I/O matrix;
- A bridge matrix converting each of the 13 consumption category into the various products for the 169 industry categories;
- Various elasticities entering the REMI PI$^+$ equations in each sector (in particular, the price elasticity of each (consumption) demand to its own price, but also many other elasticities governing the response of each industry and region to the various prices of the production factors), and
- Prices of some inputs (in particular final energy carriers).

For a policy simulation, REMI PI$^+$ accepts a large number of "shocks" in the form of Policy Variables (PV). Each PV represents an exogenous change in one REMI PI$^+$ variable such as a price, resource, investment, cost, etc.
There are many outputs within PI$^+$. Those directly relevant to the linkage with MARKAL are as follows:

- Industrial outputs in real terms;
- Household budget splits (energy, housing maintenance, transport, all other goods),

REMI PI$^+$ provides many other outputs not directly relevant to MARKAL (wages, employment, consumption, etc.), which provides the complete economic picture of energy and environmental policies.

V. THE REMI-to-MARKAL LINKAGE

In this linkage, the REMI PI^+ model is used to produce reference forecasts for the MARKAL demands for energy sectors, as well as price elasticities of demands. In addition, the two models should ideally make the same assumptions regarding the uses of energy forms by all sectors of the economy. The next three sections address these three issues.

Providing the MARKAL Reference Demands

The concept of output (in REMI PI^+) corresponds to that of demand (in MARKAL), i.e. the production of some industry or other sub-sector. This section is concerned with deriving the MARKAL demands from the REMI PI^+ outputs.

The basic approach consists of using the part of the REMI PI^+ forecast concerned with real industrial output and real household consumption, in order to construct the various MARKAL demands for energy services. Since the initial year's MARKAL demands are available from standard statistical sources, only calculated growth factors need to be derived from the REMI PI^+ outputs. In PI^+, there are 169 identified industries for which the output is calculated as part of the REMI PI^+ reference forecast. In addition, there are 79 consumption categories, but these are further spanned into the industries by means of the bridge matrix, with the result that there are up to 169 identifiable industry-level consumption categories as well. At the MARKAL receiving end, the EPA-NM has 38 demand categories that must be provided out to 2050. Thus, a transformation algorithm must be identified that will map the 169 industrial outputs of PI^+ to the smaller number of demands typical in a MARKAL model.

Besides the basic mapping of the individual industries to demands, a decoupling factor (a_{ij}) must be provided that reflects any difference between the industrial output and the related growth of the energy component. For instance, the growth of the demand for commercial lighting may be different from the overall growth of the commercial sector. This factor is equal to 1 if the MARKAL demand is expressed as the actual activity.

An ideal situation exists when one REMI PI^+ output corresponds to exactly one MARKAL demand category. Unfortunately, such 1-to-1 mappings exist for only 5 of the 38 MARKAL demands. Therefore, there is a need to address all possible situations for the derivation of the sub-sector growth factors, which may be classified in four groups.

- Group A: 1-to-1 correspondence occurs when a particular REMI PI^+ output corresponds to exactly one MARKAL demand category. This is the case for the following 5 MARKAL demands: pulp and paper, iron and steel, chemicals, air transport and marine transport. The formula for obtaining the MARKAL growth factors is:

$$\frac{DM_{k,t}}{DM_{k,0}} = \frac{a_{k,t} \times OUT_{k,t}}{a_{k,0} \times OUT_{k,0}}$$

where

$OUT_{j,t}$ *is REMI's real output for subsector j at time t.*

$DM_{k,t}$ *is MARKAL's demand k at time t.*

$a_{k,t}$ *is a factor for decoupling activity growth from energy service growth for demand k.*

- <u>Group B: Many-to-1 correspondence</u> occurs when several REMI PI$^+$ outputs together constitute one MARKAL demand category. This is the case for three MARKAL demands: the non-ferrous metals (2 PI$^+$ industries), for other manufacturing industries (84 PI$^+$ industries), and for non-metallic minerals (5 REMI PI+ industries). The formula is as follows:

$$\frac{DM_{k,t}}{DM_{k,0}} = \frac{a_{k,t} \times \sum_{j \in S_k} OUT_{j,t}}{a_{k,0} \times \sum_{j \in S_k} OUT_{j,0}}$$

where

$OUT_{j,t}$ *is REMI's real output for subsector j at time t.*

$DM_{k,t}$ *is MARKAL's demand k at time t.*

S_k *is the group of REMI subsectors corresponding to MARKAL demand k.*

$a_{k,t}$ *is a factor for decoupling activity growth from energy service growth.*

- <u>Group C: 1-to-many correspondence</u> occurs when one REMI PI$^+$ output corresponds to more than one MARKAL demand category. This is the case for residential buildings, which have 6 demands in MARKAL, but only one REMI PI$^+$ source, namely household related activity. For this sector, the PI$^+$ output will only provide an indicator for the growth of the whole sector, and additional data sources will be used to breakup this indicator into individual growth rates for each MARKAL demand category in the sector. The formula is as follows:

$$\frac{DM_{k,t}}{DM_{k,0}} = \frac{a_{k,t} \times OUT_{j,t}}{a_{k,0} \times OUT_{j,0}}$$

where

$OUT_{j,t}$ *is REMI's real output for subsector j at time t, where j is the relevant REMI subsector for the group of MARKAL demands considered*

$DM_{k,t}$ *is MARKAL's demand k at time t*

$a_{k,t}$ *is a factor for decoupling activity growth from energy service growth for demand k.*

- <u>Group D: Many-to-many correspondence</u> occurs when several REMI PI$^+$ outputs together constitute several MARKAL demand categories. There are 18 MARKAL demands in this group, constituting two disjoint subgroups. The most significant one includes the demands of the commercial buildings of MARKAL. In REMI PI$^+$, commercial activities are covered by 64 industries, but once the outputs from these 64 industries are summed up, they constitute a single commercial indicator, whereas MARKAL distinguishes 13 commercial demand categories (space heating, water heating, space cooling, refrigeration, mechanical, lighting, etc.), which are not distinguished by PI$^+$. The other subgroup is made up of 5 of the 7 transportation demands of MARKAL, excluding air and marine (i.e. car, heavy trucks, buses, freight rail, and passenger rail). These are covered by 5 PI$^+$ sub-sectors (household transport, sightseeing, rail, all trucks, and mass transit). The formula for calculating each MARKAL demand from the REMI PI$^+$ outputs is as follows:

$$\frac{DM_{k,t}}{DM_{k,0}} = \frac{a_{k,t} \times \sum_{j \in S_T} f_{j,k,t} \times OUT_{j,t}}{a_{k,0} \times \sum_{j \in S_T} f_{j,k,0} \times OUT_{j,0}}$$

where

$OUT_{j,t}$ *is REMI's real output for REMI subsector j at time t*

$DM_{k,t}$ *is MARKAL's demand k at time t*

S_T *is the group of REMI subsectors corresponding to the set T of MARKAL demands of* interest

$f_{j,k,t}$ *is the fraction of MARKAL* sec*tor demand k that corresponds to REMI* sec*tor j at time t.*

Note that : $\sum_{k \in T} f_{j,k,t} = 1$ *for all j and t. These factors are obtained from exogenous sources.*

$a_{k,t}$ *is a factor for decoupling activity growth from energy service growth for demand k.*

Note: In the event that the data available from other sources are not sufficiently detailed to obtain $f_{j,k}$ factors that are specific to each REMI PI$^+$ sub-sector *j,* one could use a single set of factors, the same for all *j*.

To illustrate Case D, let us consider the five transport demands: car travel, heavy trucks, buses, freight rail, and passenger rail, constituting set T. The corresponding REMI PI$^+$ sub-sectors are: rail transport, trucks/couriers, transit, scenic/sightseeing, and household transport (which includes personal cars and light trucks). A hypothetical but plausible set of incidence coefficients is shown in Table 4. For instance, this table indicates that 85% of ground passenger transit consists of bus transit and 15% of suburban train.

Table 4: Incidence coefficients for a set of Case D demands

MARKAL demand	**Bus**	**Heavy trucks**	**Private Cars**	**Freight Rail**	**Passenger Rail**
REMI PI sub-sector					
Rail transportation				0.9	0.1
Truck transport, couriers, messengers		0.93	0.07		
Transit, ground passenger transport	0.85				0.15
Scenic, sightseeing transport, support act	1				
Household road transport	0.18		0.75		0.07

Providing the Own-Price Elasticities of Demands

An important initial remark is that the harmonization of REMI PI$^+$ and MARKAL elasticities is essential only if the two models are used in a non-iterative manner. If on the contrary the two models are (a) linked in both directions, and (b) run iteratively until a termination condition is reached, then we shall see in section 5 that elasticities need not be identical in the two models (although identical or similarly valued elasticities would be likely to decrease the number of iterations needed).

MARKAL uses (optionally) constant own price elasticities of each demand in its computation of the equilibrium. This means that, all things equal, the following relationship holds between a quantity produced ***Q*** and its own price ***p***, with ***E*** equal to the said price elasticity (***E*** is negative):

$$Q = p^E \qquad (1)$$

Which may be rewritten:

$$\frac{\partial(Q)/Q}{\partial p/p} = E \qquad (2)$$

In REMI PI$^+$, the price reaction of outputs is not explicitly modeled via an explicit price elasticity, except in the case of consumption by households. It is still true however that PI$^+$ responds to price changes by changing outputs, but this response is governed by implicit changes, rather than by explicit formulas.

Therefore, the rigorous derivation of MARKAL explicit elasticities from PI$^+$ implicit elasticities is not possible. One could thus conclude that MARKAL should be run without price elasticities, but such a choice amounts to setting price elasticities to 0, which is certainly the wrong value. Our recommendation is to use "reasonable" price elasticities in MARKAL, without trying to match them with REMI PI$^+$'s implicit elasticities. Fortunately, as we shall see in section 5, the determination of MARKAL elasticities need not be fully harmonized with REMI PI$^+$'s; iterating between the two models will insure that the sub-sectors' activities converge in the two models.

Harmonizing MARKAL and REMI PI$^+$ Energy Production and Uses

The third and last set of variables that are possible candidates for harmonization in a REMI-to-MARKAL linkage are the quantities of energy produced and consumed by each sub-sector. However, this harmonization is not an absolute necessity, and failing to fully harmonize energy in the two models will not negatively affect the coherence of the linkage.

For REMI PI$^+$, energy is not the main focus, and its representation is fairly succinct. Only three forms of energy are explicitly recognized by PI$^+$: natural gas, electricity, and residual (petroleum). Each of these energy types are included as a value added factor, and consumed by each REMI PI$^+$ industry (and by households as well). Hence, the PI$^+$ matrix of energy production and use is a 3 X 169 matrix.

On the other hand, energy is the main sector MARKAL is concerned with (both production and consumption). There are more than 200 energy forms explicitly represented in the EPA-NM model, and each physical energy form has its own balance equation and its own endogenously calculated price. Each of these energy forms may be produced by many technologies, and consumed by many other technologies, in both supply and end-use sectors. Hence, the MARKAL matrix of energy production and use has vast dimensions.

This important difference between the two models indicates that harmonization of energy quantities cannot be precisely accomplished. However, this should not constitute a major obstacle to the R2M linkage. More precisely:

- Some existing final energy forms (refined oil products, coal, biomass), and all new future energy forms (hydrogen, alcohols, etc.) are outside the scope of fuel harmonization. Therefore, MARKAL must use other sources of information for the detailed calibration of these fuels because they are not modeled explicitly in REMI PI$^+$.
- Many primary or intermediate energy carriers used to produce electricity or heat are not represented in REMI PI$^+$ (wind, hydro, steam, solar, nuclear, etc.) and therefore do not require harmonization with PI$^+$. For these too, MARKAL may use other sources for calibrating the Reference case, without endangering the harmonization.
- The harmonization is therefore limited to the broad fuel categories of: oil products, electricity, and natural gas. Total energy will therefore not be the same in the two models, since some energy forms are ignored by REMI.

In REMI PI$^+$, the **production** of each of the three energy forms corresponds to an industry. The **use** of the three energy forms by industries and households is governed by I/O coefficients and by the bridge matrix, which are expressed in *real$input/real$output*, whereas in MARKAL, the units are physical. However, since only the growth factors of the various consumptions are needed, there is no problem using different units in the two models.

In the U.S. REMI PI$^+$, the I/O coefficients are forecasted by the Bureau of Labor Statistics out to 2018, and forecasted out to 2050 by REMI.

Conclusion:

1. With these caveats in mind, it will be possible, starting from REMI PI$^+$'s I/O and bridge matrix coefficients, to compute the rate of growth of production of each of the three broad energy forms, as well as the rates of growth of the use of each energy form by each industry and by household activities (residential buildings and personal transportation). Note that for the energy calibration, the aggregation of the REMI PI$^+$ sub-sectors into MARKAL sub-sectors would be done in very much the same way as was described in section 4.1 for calibrating the MARKAL demands. Here too, some exogenous coefficients would be needed in Cases C and D.
2. Note that harmonization may be done in either direction, i.e. either by using REMI PI$^+$ I/O coefficients to calibrate MARKAL or to modify PI$^+$'s I/O coefficients if they are deemed incompatible with some other preferred source of energy calibration.

Generic M2R Linkage Algorithm

In this linkage, the MARKAL model is used to simulate some energy/environmental policies and measures. Then, the MARKAL run results (or part thereof) are sent to REMI PI$^+$ to characterize the broader economic impacts of the simulated policy/measures. One key design feature of this linkage is the selection of the MARKAL results to be sent to PI$^+$. Another key feature is whether or not the REMI PI$^+$ results should be sent again to MARKAL for further iteration(s). The M2R linkage follows the generic linkage algorithm described here.

M2R Algorithm

Step 1: Identify the linking variables, i.e. the subset of MARKAL results to send to REMI PI^+
Step 2: Identify the REMI PI^+ policy variables and other parameters that are affected by the MARKAL results.
Step 3: Perform a MARKAL policy run.
Step 4: Set the REMI PI^+ policy variables and other parameter changes that reflect the MARKAL results.
Step 5: Run a REMI PI^+ simulation with these changes and obtain REMI PI+ results.
Step 6: **IF** {REMI PI+ results concerning sub-sectors outputs are close to the same quantities used in the MARKAL run}
THEN STOP
ELSE - Alter the MARKAL inputs (demand levels) to reflect the new REMI PI^+ Outputs
- **GO TO** step 3

Steps 1 and 2 are crucial, but done only once. The key running steps are 4, and 6. **Note that step 6 requires an application of the R2M linkage discussed in section 4**. Step 1 requires careful selection of the MARKAL quantities to be passed to REMI PI^+, with the aim to fully reflect the energy system impacts of the simulated policies without double counting. Step 4 is the actual implementation of steps 1 and 2 in REMI PI^+. Steps 1 and 2, and thereby 4, are closely associated. In what follows, we explore a few alternative choices of the linking variables (step 1) and of the PI^+ "handles" needed to convey these results to PI^+ (step 2), and their inter-relationship (step 4).

Criteria for Choosing Linking Variables

There are three main criteria for choosing a good set of linking variables:

- Criterion 1 (completeness): the linking variables should reflect all—or most, of the information produced by a MARKAL Policy Run;
- Criterion 2 (non redundancy): the selected outputs should not induce double counting of some economic effects by REMI PI^+
- Criterion 3 (implementability): the linking variables should be transferable to REMI PI^+ (either through PI^+ Policy Variables, or through changes in other PI^+ parameters).

A Proposed Set of Linking Variables

For linking variables, we choose the entire set of primary MARKAL results mentioned in figure 2.2, and repeated below. Only the **changes** in these quantities relative to the MARKAL Reference case and relative to a base year are transferred to REMI PI^+.[2] The linkage variables are:

- Fuel quantities produced, imported, and exported, expressed in real terms (each fuel: crude oil, natural gas, electricity, coal, biomass, refined oil products, alcohol, hydrogen);
- Fuel quantities consumed by each industry and household sub-sector, expressed in real terms;

[2] For instance: if electricity production is 2000 TWh in year 2005, reference case, and 2200 TWh in 2010, (reference case), and if it is 2300 TWh in 2010 (policy case), then the respective growths are 10% and 15%. Therefore, only the difference in growth is passed to REMI, i.e. +5% in 2010. REMI may now re-convert this 5% into its own units of output for this industry.

- Energy related investments in each MARKAL sub-sector (energy producing industries, energy consuming industries, residential equipment, personal transportation) expressed in real dollar terms;
- Non-fuel annual expenditures incurred by each industry and each residential and commercial activity, expressed in real dollars
- Changes in fuel (marginal) prices

The completeness criterion is fully satisfied, since the selected linking variables include all of MARKAL's primary results[3].

The non-redundancy criterion will be satisfied *provided REMI PI$^+$ does not further modify the quantities that are passed on by MARKAL*. This is verified for energy prices (which are exogenous in REMI PI$^+$). On the other hand, in a normal policy simulation, REMI PI$^+$ would further modify the quantities of fuels consumed by industries and by households, since these PI$^+$ sub-sectors are sensitive to energy prices. This difficulty can be remedied *by reincorporating these value-added factors into intermediate industries*. Thus, energy would no longer be a substitutable factor of production (alongside capital and labor); all direct energy use coefficients would be set at a fixed proportion of industry use for each year. This fixed proportion could be changed in the base forecast by using elasticities from the M2R linkage. The MARKAL specialized industries that are part of one or several REMI PI$^+$ variables can be represented by translator variables. Cost changes in the energy prices will be represented using their fixed proportion of the total production technology in the input-output matrix.

The implementability criterion: there are viable ways to pass on the MARKAL linking variables to PI$^+$, as described here.

- Energy prices may be passed directly as parameters.
- Quantities of each energy form produced are indeed akin to REMI PI$^+$ real outputs by several industries. The use of REMI PI$^+$'s translator variables make it possible to specify to REMI PI$^+$ by how much each such energy supply industry's output is changed as a result of the MARKAL policy run.
- When converting MARKAL investments, fuel consumptions, and non-fuel expenditures, the same mapping issues that were discussed in section 4 crop-up again. Each of the four Cases identified in the R2M linkage will also occur and may be treated in exactly the way described in section 4.

The Complete M2R Algorithm

Regarding Step 6, one must first develop a tolerance level, below which the difference between two successive sets of MARKAL demands are judged to be sufficiently close to stop the algorithm.

We now turn to the issue of iterations: in theory, if the two models were 100% coherent in the way they respond to economic stimuli, iterating would not be required: indeed, using price elasticities of outputs that are fully harmonized between the two models would entail that the adjustment of MARKAL demands, and the subsequent PI$^+$ adjustment of its sub-sectors' outputs, would be identical, and thus the algorithm would stop at the first iteration. In reality, such an ideal outcome is unlikely, since it is difficult to harmonize the sectors and their price elasticities between the two models, as discussed in section 4. *However, it is still useful in the context of harmonizing the models and*

[3] Another MARKAL result readily available relates to emission sources, levels and prices (if limits or taxes imposed), which could be passed to REMI or some other framework as part of air quality and health impacts analysis.

reducing iterations to run MARKAL with non-zero price elasticities at least approximately harmonized to those of PI^+, even if the values of these elasticities are not directly obtained from REMI PI^+.

We conclude that iterations between the two models are likely to be needed. The stopping criterion could be that the MARKAL demands obtained for two successive runs are sufficiently close to one another.

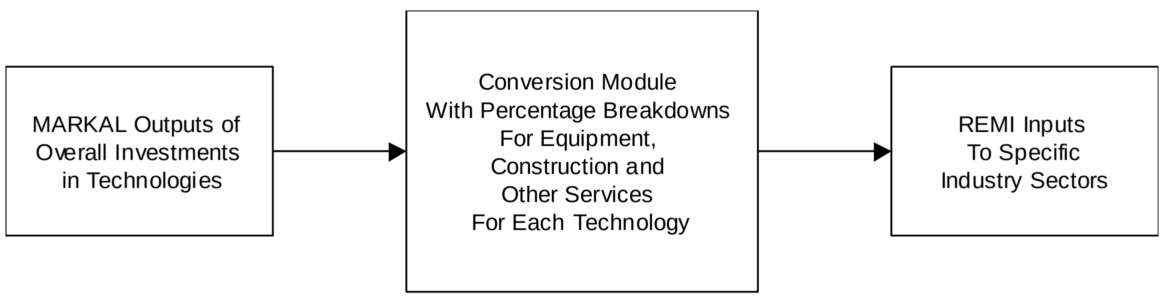
An Additional Refinement

One aspect of MARKAL results has been ignored in the above linkage algorithm, namely the detailed nature of the technology investment decisions taken by MARKAL. For instance, if the MARKAL response to a certain energy policy is to replace coal fired power plants by wind turbines and gas plants, these decisions have implications with respect to the industries that manufacture the equipment (e.g., gas turbines, wind turbines, etc.) and those that provide services (e.g., engineering, construction, project management, etc.) These changes will in turn have impacts on other industries (through the I/O matrix) and eventually on labor, employment, etc.

However, MARKAL quantifies only the new capacity of power plants and other investments in new technologies. It does not explicitly produce estimates of the breakdown of these investments into equipment, construction, and services requirements. Therefore, to capture this effect, one would have to externally determine these quantities for each of the conversion, process and end-use technologies in MARKAL so that the MARKAL investment plan can be translated into specific REMI PI^+ sector inputs. This task would be performed outside MARKAL or PI^+, and injected in to PI^+ as an additional policy change (perhaps in the form of new I/O coefficients or some other REMI PI^+ input changes). Figure 2.4 sketches the procedure.

The adoption or not of this additional refinement is an additional decision to be made regarding the linkage. Its importance is *a priori* uncertain, and should be assessed as part of the next phases of the project.

Figure 2.4: Mechanism for injecting equipment decisions into REMI PI^+



VI. REMI-MARKAL INTEGRATION

Economic Impact of Ethanol Subsidies in the United States

Introduction

This section outlines a study using integration between the REMI PI$^+$ regional impact and MARKAL energy models. Like many developed countries, the United States subsidizes its agricultural industry, its corn producers, and in particular, its ethanol producers. This policy, codified as the "Renewable Fuel Standard" (RFS), began in 2006 to promote the development of corn ethanol, cellulosic ethanol, and bio-fuels from domestic sources.[4] The RFS marked a large expansion of other programs dating back to the Oil Crisis of the late 1970s. The program has many dimensions, including federal funding for research and development, grants and loan subsidies for bio-fuel producers, tax credits and subsidies for alternative fuel production, and mandates on conventional fuel producers to include ethanol and related bio-fuels in traditional gasoline and other fuels. The scope of the mandates and production requirements continue to grow into the rest of the 2010s and the 2020s.

These policies have considerable influence on food, fuel, and energy markets, which the MARKAL model can quantify with proper data. MARKAL's outputs then combine with the PI$^+$ framework—which includes the additional aspects of energy policies, including taxes, government subsidies, production costs, and the associated—to give a macroeconomic description of the impact of a policy like an RFS. This report combines one such MARKAL study with the REMI framework to provide such analysis. The MARKAL data comes from "Analysis of US Renewable Fuels Policies Using a Modified MARKAL Model" by Kemal Sarcia and Wallace E. Tyner of Purdue University.[5] Their study used data from the National Academy of Sciences to describe the technology potential of corn and cellulosic ethanol from 2010 to 2030 and a MARKAL model (with inputs from a land-use model to quantify the effects of ethanol on traditional food-producing agriculture). From there, they predicted the influence of bio-fuels on American energy production and fuel markets to 2030, in light of government incentives.

Methodology

This study takes Sarcia and Tyner's MARKAL data and translates it into the framework of the REMI models using the processes outlined in the technical memorandum. For instance, Sarcia and Tyner provide data on the estimated electricity production from ethanol fermentation. This goes into PI$^+$ as decreased production cost for chemical manufacturing (which includes ethanol in the North American Industry Classification System - NAICS codes)[6] due to electricity resale. This also results in decreased industry sales for electrical generation to offset the difference and balance the model. Oftentimes, Sarcia and Tyner only provided data in either ten-year or five-year increments. In those cases, the approach used a linear extrapolation to "fill in the gaps" between years and to continue the study. This section includes an outline of the policy variables harnessed from MARKAL data, a description of their treatment, other variables needed to balance model inputs and outputs, and results of the simulation.

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[4] For a description of the beginning of the program, please see the following *Wall Street Journal* article from December 14, 2011: <http://online.wsj.com/article_email/SB10001424052970204012004577072470158115782-lMyQjAxMTAxMDEwMzExNDMyWj.html?mod=wsj_share_email_bot>. Do note, the second half of this article includes editorial commentary besides the "dollars and cents" in the outline of the actual program components.

[5] The full report, as funded by the United States Department of Agriculture, is available free online: <https://www.gtap.agecon.purdue.edu/resources/download/5371.pdf>.

[6] NAICS is the North American Industrial Classification System, which is the organizing principle of the industry combinations in PI+, <http://www.census.gov/eos/www/naics/>.

This study uses the so-called "Census Regions" model, which includes 9 regions and 169 sectors from the NAICS. The United States Census Bureau developed the regions for reporting its demographic information based on overall patterns.[7] Spreading the inputs to the model by the underlying data in the baseline (for example, spreading additional grain output by the proportion of previous grain output, by region, in the baseline), the study analyzes the policy at the national scale. The regional combinations and industrial sectors might change in non-American models, but this covers the same policy variables and integration process.

Policy Variables

The variables for this simulation and from the MARKAL data fall into five broad categories. This gives a fuller description of the model for the regional model:

1. Corn ethanol production and costs—from Sarcia and Tyner
2. Cellulosic ethanol production and costs—from Sarcia and Tyner
3. Government subsidies[8] to incentivize ethanol production
4. Changes to electrical power generation and environmental or amenity benefits/costs
5. Impacts on the farm sector, as well as food and fuel prices

The rest of this section describes the specific policy variables from MARKAL to REMI.

Corn ethanol production and costs

- **Industry Sales (chemical manufacturing)** – This data comes from MARKAL, and it reports the expected sales (the price times the quantity produced) of the ethanol industry.
- **Nullified Investments (chemical manufacturing)** – Sarcia and Tyner reported the necessary capital investment, by year, to develop the needed infrastructure to fulfill the RFS policy. Therefore, we nullified the induced investments generated automatically in the model, and added them manually with another policy variable.
- **Non-Residential Capital Investment** – This variable manually added the investment from the ethanol infrastructure, which the model normally does on its own, but we selected the option to do it from the MARKAL technological data in this instance.
- **Exogenous Demand (chemical manufacturing)** – This represents the O&M costs reported from the MARKAL model for corn ethanol. Chemical manufacturing is the best industry to symbolize O&M for other chemical manufacturing, as it includes similar intermediate inputs and labor requirements, rather than generic construction. Exogenous demand implies "subcontracting" between different industries, and allows purchases from other regions or even from other countries, depending on the cheapest price.
- **Farm Output (grain farming)** – MARKAL reported expected liters of ethanol production, kilograms of corn needed per liter of ethanol, and the price of corn over time. Since corn ethanol production requires a large input of agricultural produce, we programmed this into the model as an increase in output and sales to proprietor farmers. Corn ethanol will put upward pressure on corn prices in the United States, but agriculture is a peculiar industry in terms of its response to crops' price changes. Namely, there are many producers, which approximate perfect competition, and farmers are "price-takers" on the market. They are, also, relatively insensitive to prices, preferring to grow certain crops based on local soil and climate conditions, as well as familial traditions. This makes them relatively unresponsive to

[7] For the regions, see here: <http://www.census.gov/geo/www/us_regdiv.pdf>.

[8] Please see p. 7 of the MARKAL report for specifics and assumptions about the government subsidy. Specifically, this report compares Sarcia and Tyner's scenario #1 ("no policy," the baseline) with scenario #3 (implementing the RFS with current policies and current technological profiles).

price fluctuations on the market, and an increase in corn prices would be a direct windfall to corn farmers and their output in the model.

Cellulosic ethanol production and costs

- **Industry Sales (chemical manufacturing)** – The data set for cellulosic ethanol from MARKAL is virtually the same as the one for corn ethanol. Here, MARKAL reported the expected prices and quantity—and therefore industry sales—for cellulosic ethanol under certain policy and technological conditions.
- **Nullified Investments (chemical manufacturing)** – As with corn ethanol, we have specific data on investments from the MARKAL model, which we include manually after nullified the model's automatic responses.
- **Non-Residential Capital Investment** – This adds the capital investments for cellulosic ethanol from the data in the outside report.
- **Exogenous Demand (chemical manufacturing)** – This models subcontracting for O&M costs for the maintenance of cellulosic ethanol production.
- **Farm Output (oilseed farming, grain farming, cotton farming, and all other crop farming)** – Different principles apply for cellulosic ethanol in comparison to corn ethanol. Corn produce goes towards feeding livestock, which means it competes with the food supply and increases costs for other farmers and ranchers. Humans and most livestock, on the other hand, cannot consume cellulose, which means it is essentially "waste material" under general farm conditions. Creating ethanol from cellulose would harness this waste material without putting an undue burden on farmers or increasing food prices. Here, we assumed that the purchase of waste material would slightly increase farm output for the related farm sectors, though not by nearly as much as related corn purchases.

Government subsidies to incentivize ethanol production

- **Federal Civilian Spending** – The PI^+ model has a number of ways to "pay for" the offset of government incentives programs. This includes cuts in other government spending priorities, including education, transportation, or healthcare, or cuts at different levels of the government (federal, state, and local). It also includes increasing taxes on income, new or heftier sales taxes, or capital, corporate income, or profits taxes on businesses. In this case, we modeled the financing of the incentives program from MARKAL as one-third from other federal spending, one-third from other state-level spending, and one-third from increased personal income taxes. The "cut" in baseline federal spending represents the redirection of federal resources away from traditional federal spending—defense, social insurance—towards paying for the one-third cost of the ethanol subsidy.
- **State and Local Government Spending** – Another one-third of the cost comes out of reductions in state and local government spending in the model. This illustrates the flexibility of the model and the interrelations between levels of government. For example, cuts in federal spending usually imply reductions in the transfers to state agencies, which PI^+ quantifies with the policy variable here.
- **Personal Income Taxes** – REMI includes a portion for the household economy, including the taxes coming out of personal balance sheets. This variable increases personal taxes, which means less disposable personal income and less consumer spending. The past three variables sum to total the government subsidy for ethanol.
- **Production Costs (chemical manufacturing)** – The subsidy goes toward reducing the costs of production for the chemical manufacturing industry. Lower production costs will

give the industry a competitive advantage—due to government transfers—and allow it to expand and gain market share in the near- and long-term. This variable also helps to balance the increased costs of production from manufacturing ethanol.

Changes to electrical power generation and environmental or amenity benefits/costs

- **Production Costs (chemical manufacturing)** – According to the MARKAL run and data, ethanol production generates surplus electricity. Hence, the ethanol industry can sell this back to the electrical grid or use it for their productive purposes, which would reduce their "drain" on the overall grid and their electricity bill. Either way, it leads to a reduction in their cost of operations, which gives them a competitive advantage over other industries in other areas and in the process of attracting investment capital.
- **Industry Sales (electrical power generation)** – Consequently, as ethanol producers make a small amount of their own electricity, this would reduce the sales to the traditional utilities industries. This enters into PI^+ as negative industry sales.
- **Non-Pecuniary Amenity** – The technology profile of the MARKAL data reports a hefty output of carbon dioxide from ethanol production. For example, in 2010, Sarcia and Tyner reported that one liter of ethanol production from corn emitted 4.93 kilograms of carbon dioxide.[9] The PI^+ model includes a factor for "amenity," which is the non-economic attractiveness of a region or the social externality costs or benefits of an action. This variable is especially relevant in the transportation field, where benefit-costs analyses about changes in vehicular emissions of gases such as carbon monoxide and sulfur dioxide go back into the model as amenity to illustrate the externality costs. On the other hand, local pollutants (such as ozone or particulate matter) are easy to imagine as a factor in local attractiveness, but carbon dioxide is harmless to humans and other creatures on the local level. Its climatic effects are harder to quantify, but a survey of sources rated the average total social cost of carbon dioxide as $43 per metric ton.[10] For demonstration purposes, we included this cost in the simulation, adjusting the amenity of emission downward (from emissions out of ethanol plants) and upward (from saved emissions from traditional utilities) accordingly. A user can utilize the amenity variable for other issues of regional attractiveness or quantify the effects of other types of atmospheric emissions.

Impacts on the farm sector, as well as food and fuel prices

- **Farm Output (grain farming)** – The previous policy variables modeled the demand for corn and cellulose from the ethanol industry as an intermediate input. At the same time, however, increase demand for corn and farm products creates a windfall for all farms in the industry, not just the ones receiving orders from ethanol producers. We modeled this "price-taking" effect for the entire farming industry by increasing total output for the types of industries, per the numbers reported by the MARKAL report.
- **Farm Output (cattle ranching and farming)** – The vast majority of corn production in the United States goes towards animal forage.[11] Hence, increased corn prices will initially hurt beef and meat producers the most before "hitting" consumer pocketbooks when they buy groceries. This is a complicated effect, and for lack of data from the MARKAL output

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[9] Please see p. 6 of their report for the exact figures and technological profile.
[10] The IPCC (Intergovernmental Panel on Climate Change) includes a survey of estimates on their website, as well as the average figure used here: <http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch20s20-es.html>.
[11] For example, see this chart, which takes its data from the United States Department of Agriculture: <http://tinyurl.com/cornuseus>.

here, we included the increased costs of corn inputs as a drain on proprietors' income. This increases the cost of corn as an intermediate input to the *other* farms that need it.

- **Consumer Price (gasoline and oil)** – The RFS requires that traditional refineries begin to include ethanol as a part of their fuel mixture. Given these figures and data from the MARKAL runs, we calculated the expected change in fuel prices due to expanded ethanol production from the RFS and the government subsidy. This goes into the model as an increase in gasoline prices for consumers, who will then, therefore and automatically, have less money to spend on other purchases. This increases the price index in the model, as well as the cost of living for households in the 2010s and 2020s.

Further Factors for Consideration

The above policy variables and inputs come from data out of Sarcia and Tyner's MARKAL scenarios and the procedures in the technical memorandum. There is, however, one other set of considerations that require outside inputs or assumptions from the model user. The investments by the chemical manufacturing industry for infrastructure development and O&M are considerably large. However, there is no means for the model automatically balances these inputs to the economy. For example, the billions of dollars of capital investment in ethanol production will make a similar amount of money unavailable for other industries or startup enterprises. This "crowding out" of capital is an important simulation, and PI^+ includes variables for production costs or capital costs by industry to consider them. The results of this simulation do not consider these issues, but they could in different model runs, depending on the exact nature of the policy or the assumptions desired by the model user.

Results

This includes the results of the above policy variables with data and numbers taken from the MARKAL runs. These outputs are some of the major highlights from the PI^+ model about the impact of the RFS on the United States' economy. On the other hand, these results concentrate, chiefly, on macroeconomic indicators such as gross domestic product (GDP) and total employment. The model, also, includes results by industry and a full demographic breakdown (at least for the models in the United States), which we will touch on in these results. The list of reported results includes all of the following metrics:

1. **Total Employment**
2. **Private, Non-Farm Employment**
3. **Gross Domestic Product (GDP)**
4. **Output—GDP including the value of intermediate inputs**
5. **Real Disposable Personal Income**
6. **PCE-Index—impacts on prices**
7. **Employment by Industry**
8. **Employment by Occupation**

Total Employment

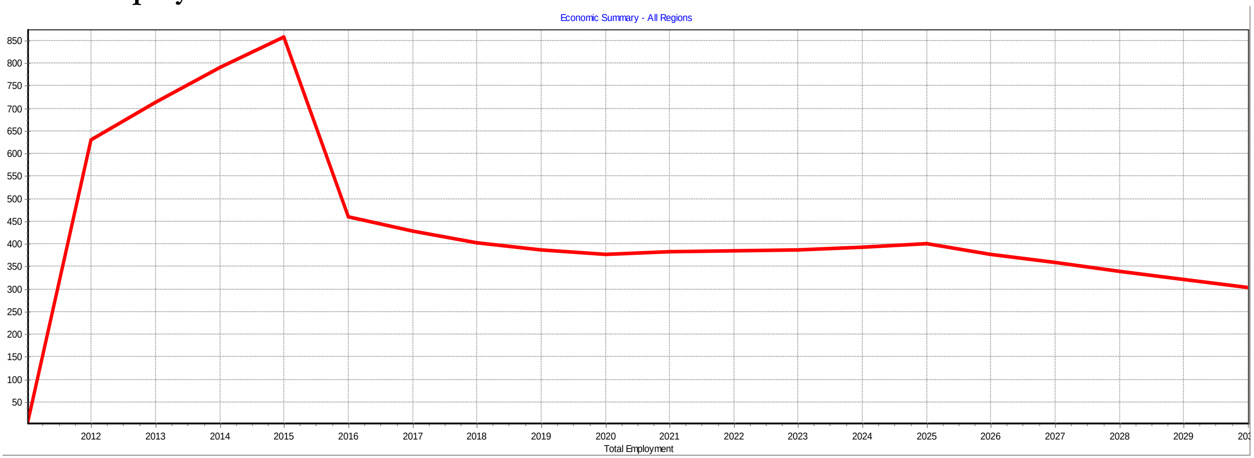

Figure 3.1 – The red line is the total increase in employment from the RFS, and the units to the left are the thousands of jobs. Hence, the RFS generates about 850,000 jobs over the baseline in its peak year of 2015. The initial spike from 2011 to 2015 is due to large amounts of investment to build ethanol capacity before production hits its maximum around 2015. From there forward, additional farm income and industry sales to chemical manufacturing drive higher employment throughout the national economy.

Private, Non-Farm Employment

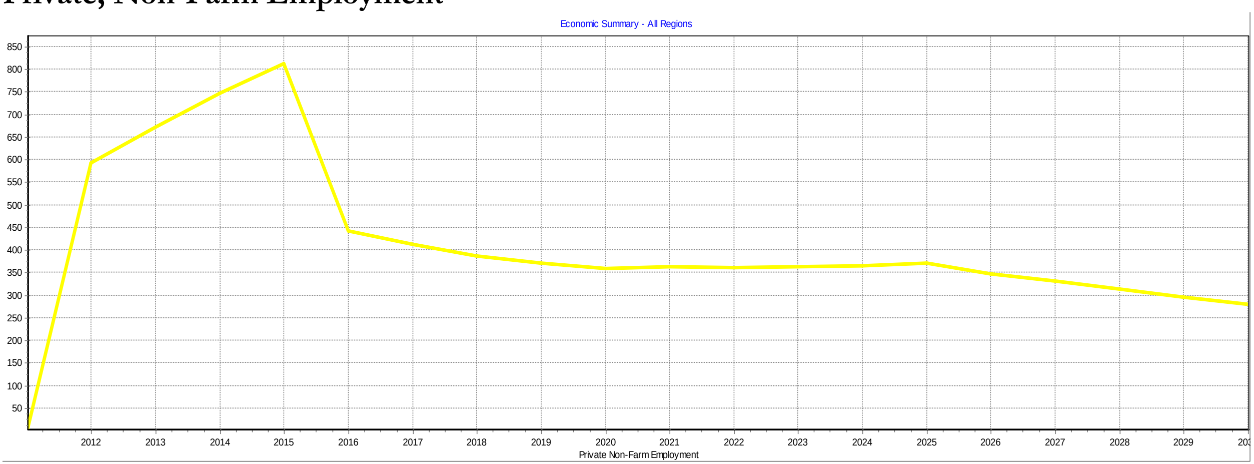

Figure 3.2 – This graph reports total private, non-farm employment from the RFS. The units and the years are the same as the previous graph. Hence, most of the employment from the policy comes on the private market, and not from government hiring, though there is some additional government employment over the private market.

Gross Domestic Product (GDP)

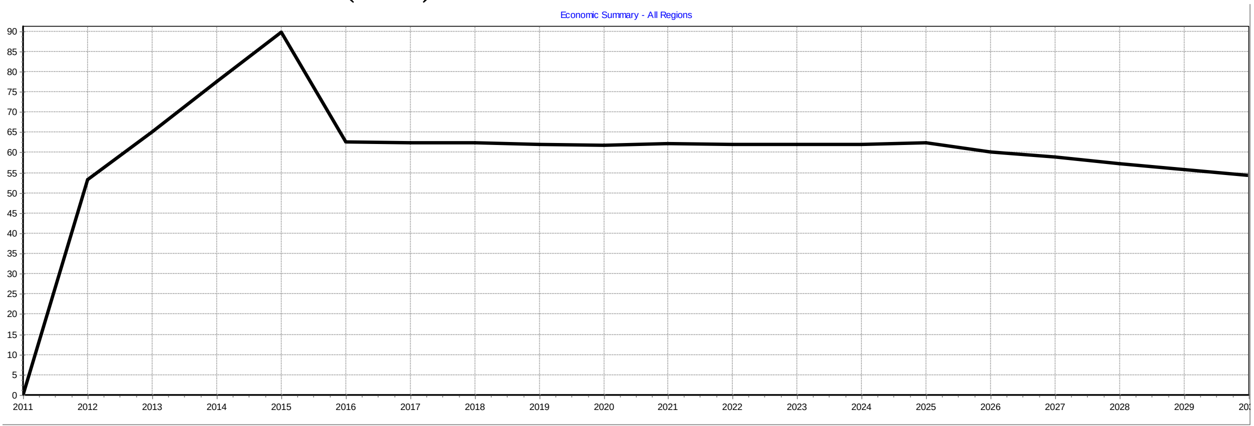

Figure 3.3 – The black line is additional GDP over the baseline, per year, in billions of 2005 dollars. The RFS creates an expansion of the American GDP here, at least, discounting the production and capital costs outlined at the end of the previous subsection. Again, the initial spike is due to the high output of the construction phase, while the longer-term influence of the project is not quite as large on the economy.

Output—GDP Including the Value of Intermediate Inputs

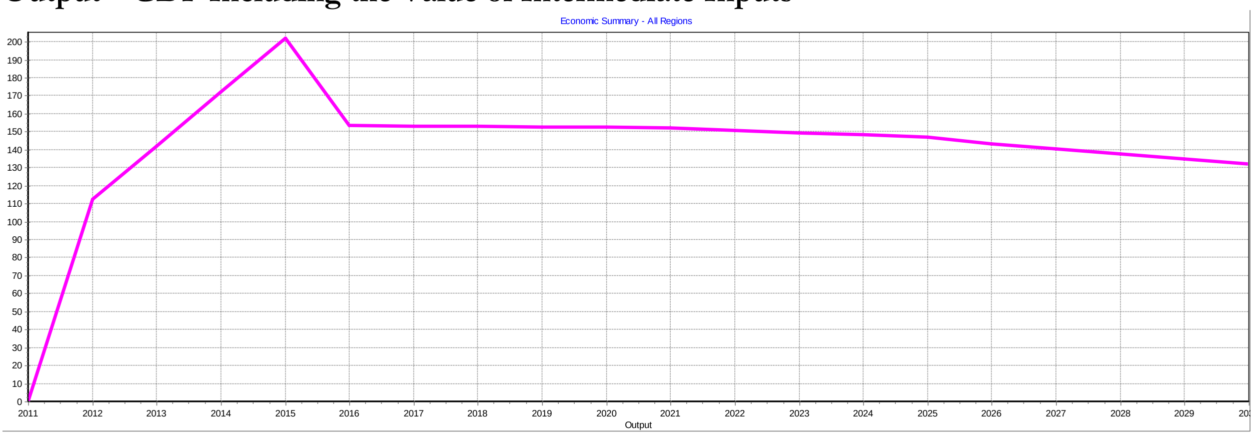

Figure 3.4 – The pink line here is total output of the United States economy over the baseline due to the RFS. The units are the same as the previous figure. Gross domestic product is the sum of industry sales when subtracting the "double-counting" of intermediate inputs, while output allows all industry outputs into the calculation, despite their use of intermediate inputs from other industries (out of the input-output table). The total additional output of the economy peaks around $200 billion in 2015, before reaching some stability in the longer-run from 2016 to 2030.

Real Disposable Personal Income

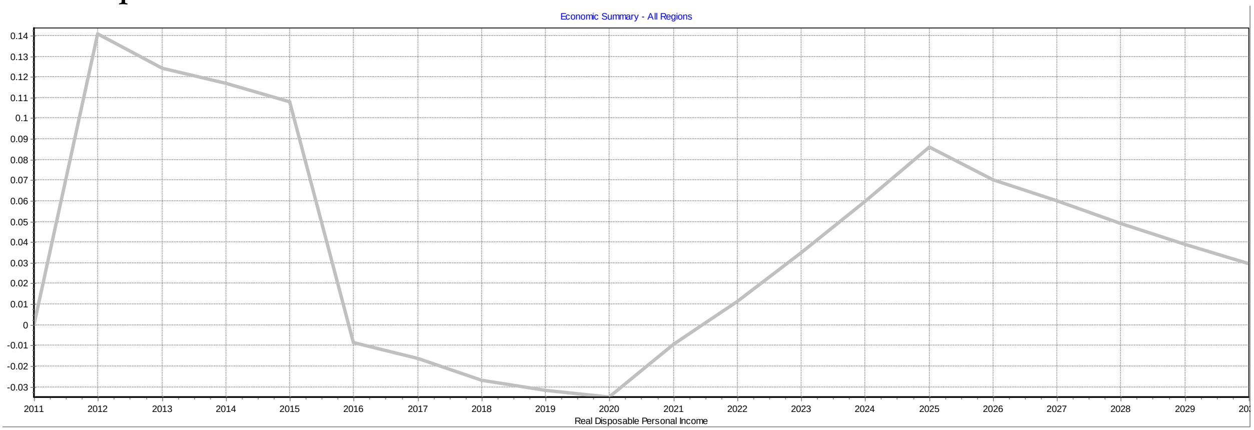

Figure 3.5 – The above graph reports the percentage change, from the baseline, for disposable personal income in the United States from the RFS. The peak impact, in 2015, is about 0.14% higher than the business-as-usual scenario without the RFS. The amount of disposable personal income in the economy is dependent on two factors: (1) total number of paychecks for the employed and (2) the cost of living. Here, additional jobs put upward pressure on the total amount of disposable income in the economy, but higher taxes, gas prices, and food prices reduce the actual purchasing power of the same dollars throughout the economy. The effect of the higher prices is enough to flatten gains to personal income in the late 2010s and reduce them throughout the 2020s.

PCE-Index—Impacts on Prices

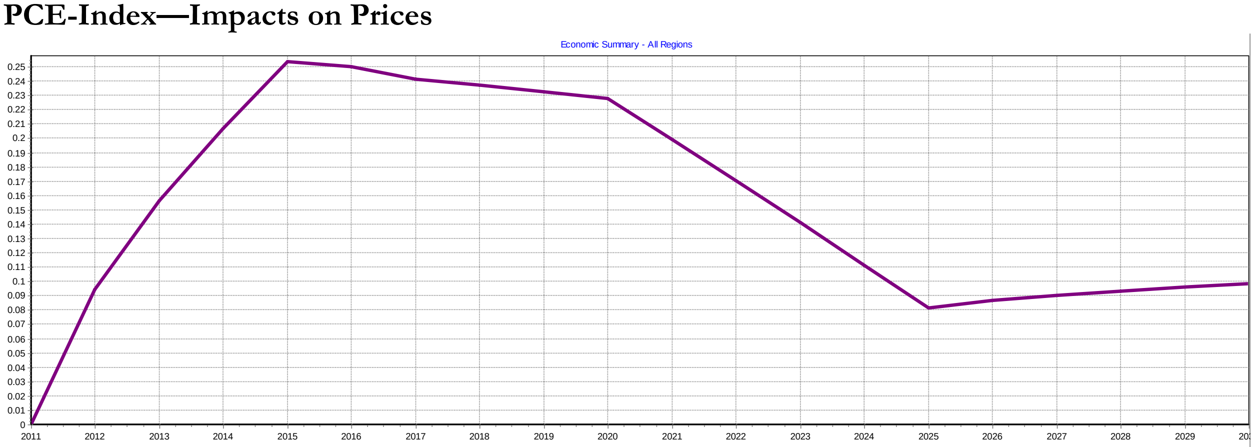

Figure 3.6 – Higher taxes and gasoline prices push the PCE-Index—the PI^{+} measurement of consumer prices into the future—upwards in the simulation. The above is the percentage change of the same. The index spikes the highest between 2015 and 2025 as gasoline prices rise the quickest over the baseline and the government pays a large subsidy to ethanol producers for a high level of production. On the other hand, the subsidy law is in nominal terms, and, therefore, inflation will reduce its impact in real terms in the future. This is, partly, responsible for the decline in the PCE-Index over time from personal taxes. Gasoline follows a similar pattern of the above line.

Employment by Industry

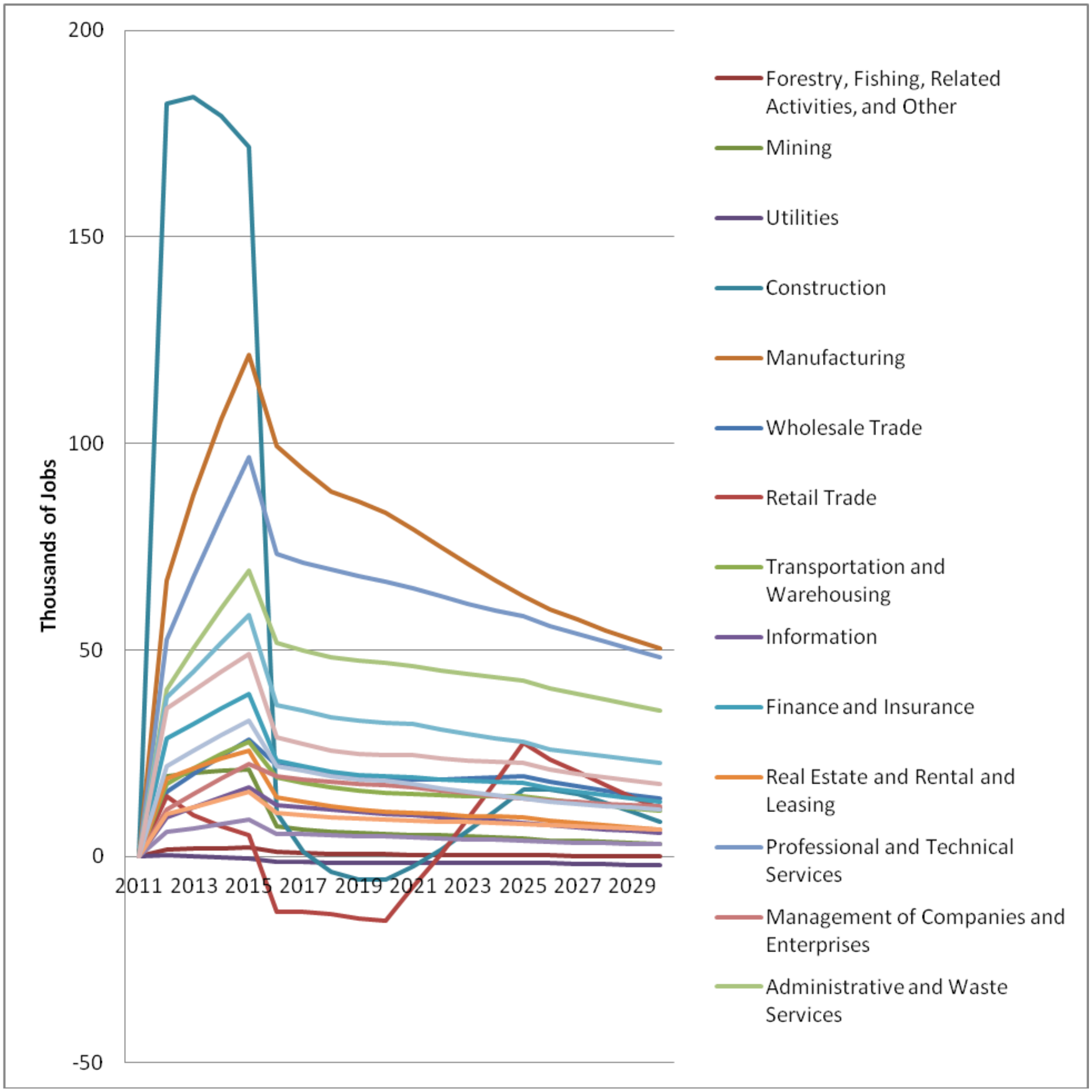

Figure 3.7 – This graph shows the impact on employment by industry. The units are thousands of jobs over the baseline, as divided by two-digit NAICS. The largest spike to the left, in blue-green, is the construction industry, which sees a massive boost from 2012 to 2015 from investment in ethanol-production infrastructure. The industries that provide the intermediate inputs for construction and chemical manufacturing—including general manufacturing, professional and technical services, and administrative/waste services—also grow quickly in response to the RFS. The red line towards the bottom, retail trade, loses some jobs due to higher gas prices (which drains consumer spending) and personal taxes at their heaviest from 2015 to 2025 (likewise).

Employment by Occupation

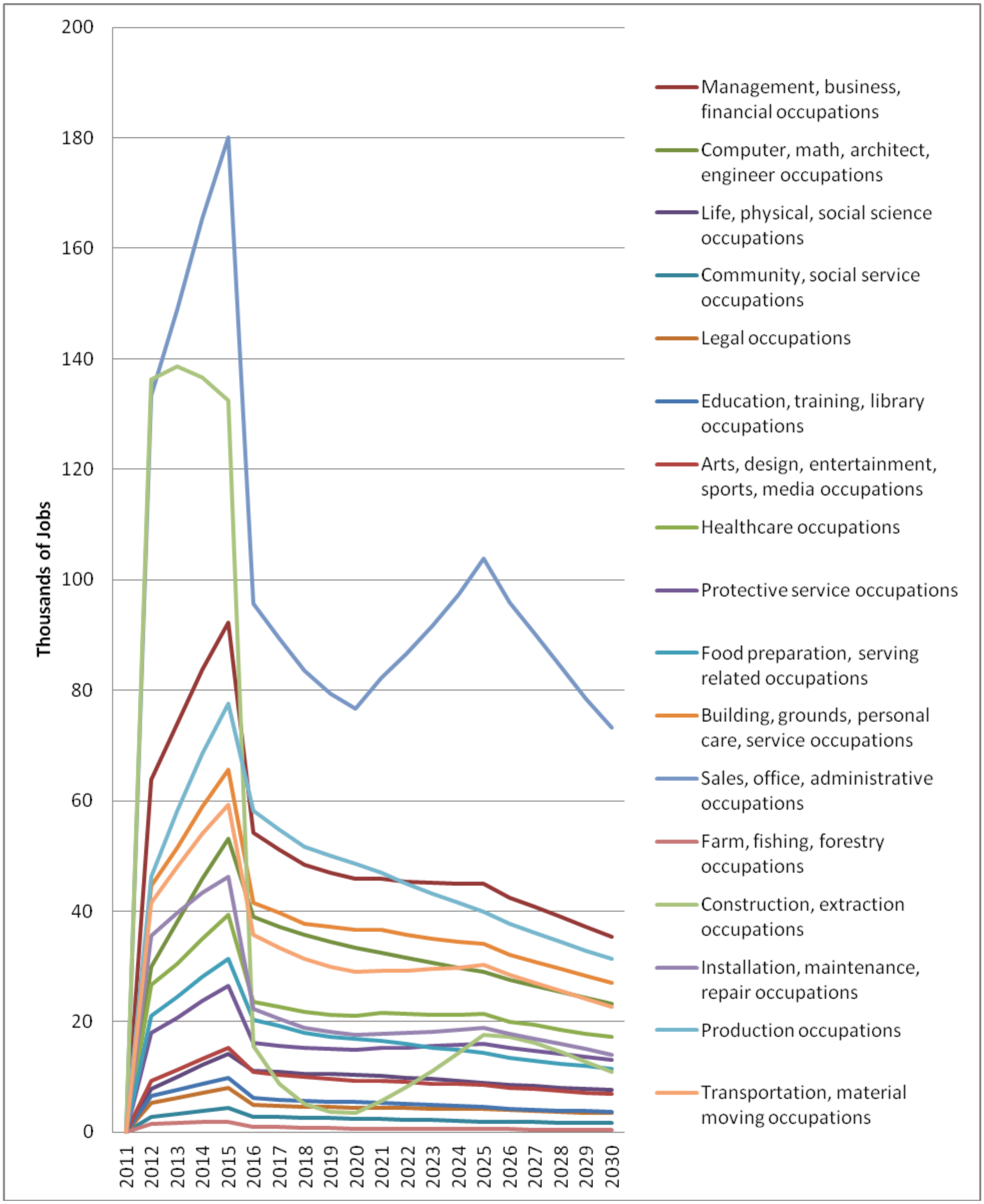

Figure 3.8 – The above is the changes to the occupational profile of the economy in response to the RFS. The units are thousands of jobs, over the baseline, by year, by category of occupations. The top light green line, which is for construction trades, obviously has a boon from the policy in the short-run, as well as office and support occupations.

These occupational developments come from the changes in the industry mix, as different industries have different hiring profiles in the PI$^+$ model. Other highlights include the red line (for management of companies and enterprises), the light blue line (for productive occupations in manufacturing), and orange (for maintenance and care of grounds, facilities, and campuses). Construction trades fall quickly after the investment stage, though they never fall below the overall baseline from 2016 out to 2030.

Conclusion

This study provides a simulation and report of a PI$^+$ result written entirely from MARKAL data. The data includes information on corn ethanol production, cellulosic ethanol production, and their place in the overall energy portrait of the United States in the future. The model run also includes government subsidies and their offsetting cuts and taxes. The model, also, from MARKAL, includes impacts on the household and farm sector in terms of prices. The results from PI$^+$ and MARKAL include major macroeconomic indicators, including employment, private employment, gross domestic product, output, real disposable personal income, and costs of living. In the deeper results are employment by industry and the occupational profile of the United States in response to the RFS. The procedures come from the outline in the rest of this paper and the technical memorandum, and it includes specific policy variables for taking data from an energy simulation or MARKAL run to do macroeconomic analysis. Hence, a user of a REMI-MARKAL integration could follow the same process to evaluate the full range of impacts of energy policies – economic, technological, and environmental.